Green Energy and Technology

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Solar Energy in the Winemaking Industry

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Foreword

"The Sun, with all those planets revolving around it and dependant on it, can still ripen a bunch of grapes as if it had nothing else in the universe to do". This quotation, ascribed to Galileo Galilei, is perhaps even more insightful when one realises that different parts of the solar spectrum are responsible for specific tasks. The photosynthetically active part that enables the growth of grapes overlaps with those parts of the spectrum that encourage their ripening. This division is mimicked by the different spectra that are employed in man-made solar energy devices producing heat and electricity respectively. The many uses of solar energy do indeed happen as if the Sun "had nothing else in the universe to do". Some uses of solar energy can seem obvious but do so only after pathfinder projects have demonstrated feasibility. The use of solar energy in wine making is one of these. Solar energy can be harnessed readily for the production of hot water and for the generation of electricity via photovoltaics. The opportunities for solar energy use vary obviously and more subtly, with climate but can be significant for relatively low temperature process heating, cooling and plant operations. That such applications are all present in wine production has presented an opportunity taken up by the 293 known "solar wineries" globally. A solar winery uses to some extent either solar thermal and/or photovoltaic energy. Of 293 installations worldwide 48% are in California and 16% are in Germany, so there is considerable scope for wider adoption. This book shows a multitude of successful example applications of solar energy to wine production. Energy efficient wine production principles that are a prerequisite before the means of energy supply is decided, this together with contemporary viticulture and oenology for an estimated 184,000 potential solar wineries worldwide means the potential for the adoption of solar energy in wine making is truly enormous. The wider adoption of the practical systems described in this book should enable some of that potential to be realised. The environmental and, in many cases, economic benefits that will ensue will be considerable. Solar energy contributes to all stages of wine production from the process

of photosynthesis to manufacture and ultimately to distribution. There is a certain harmony in solely harnessing nature when making wine that this book will help to realise.

Dublin, 2011 Brian Norton

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Introduction to the Solar Winery

1.1 Introduction

Climate change and its potential impact is one of the greatest challenges facing mankind today. Viticulture and winemaking, much like the ski industry, are climate change bellwethers as both are highly dependent upon the weather, climate and place. Any future changes in the seasons, their duration, local maximum, minimum and mean temperatures, frost occurrence and heat accumulation could have a major impact on the winegrowing areas of the world. These changes are already evident in the form of increased vineyard plantings in what were a number of years ago thought to be marginal regions, such as southern England, or the movement of 'traditionally warmer' varietals into new 'cooler' regions (Fig. 1.1).

Winegrowing (viticulture and oenology) is a global industry, representing a significant demand on the world's resources, including fossil fuels. In 2009, 7,660,000 ha (18,920,000 acres) were under vines [1] producing 268.7 million hectolitres of wine [1]. Even though the production and transport of wine only makes up 0.08% of global green house gas emissions or about 2 kg/0.75 l bottle, the industry has a great deal at stake [4]. It could be argued that the winegrowing industry given its energy requirements, subsequent emissions and the detrimental effects that climate change may bring to the industry, should be at the forefront in promoting the case of energy efficiency and the adoption of renewable technologies. Solar renewables in the form of solar thermal and photovoltaics (PVs) offer a complimentary solution to many winegrowing processes and in recent years have given rise to the concept of the 'solar winery'.

1.1.1 The Concept of the Solar Winery

The modern definition of the solar winery would require that the building or processes involved in winemaking in some way (directly or indirectly) makes use of solar energy 'actively' collected from radiation incident upon the vineyard or

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Fig. 1.1 The successful Denbies winery in the south of England

winery. Of course it could be argued that the concept of the solar winery is nothing new, in fact solar energy has always played a very important part in winemaking—the sun's energy is necessary to produce the key ingredient; grapes. Indeed most winery buildings do 'passively' utilise the sun's energy through heat gain or daylight to a lesser or greater extent. Moreover, the penetration of stand-alone solar powered equipment has been used in vineyards and wineries for years, as shown in Fig 1.2. But large scale 'active' solar collection is a relatively recent development, one that has the potential to have a very positive impact on the industry, its energy usage and carbon footprint.

To be able to produce grapes for wine, a particular climate is required. Most of the world's wine producing regions are found within the temperate latitudes of 30 and 50° in both hemispheres with annual mean temperature ranges between 10 and 20°C, constantly changing seasons with moderately variable conditions and around 700 mm of rainfall throughout the year. In addition the requirement of 1300–1500 h of sunshine during the growing season implies that most wineries are located in regions where the solar resource is highly favourable.

These climatic factors, the multitude of buildings with suitable mounting surfaces coupled with the increasing cost of fossil fuel derived energy and the subsequent environmental impacts that using such fuels creates, makes solar renewable technologies an important alternative source of energy for winemaking. Having a suitable climate, location and economic or environmental incentive, whilst essential, are not the only factors that must be considered. There must either be an all-year-round energy demand or an effective means of energy export or storage to ensure that any collected solar energy is effectively utilised. Fortunately,

Fig. 1.2 Small scale stand-alone solar operation

in most wineries, there is a continual (albeit fluctuating) energy demand, one that can easily adapt to make use of the many forms of solar energy collection.

1.2 Environmental Drivers

As previously mentioned, most of the world's wine producing regions are found within the temperate latitudes of 30 and 50° in both hemispheres, though altitude and proximity of large bodies of water can impact the micro-climate. Figure 1.3 illustrates the global location of significant wine producing regions (black shading) and the average annual temperature isotherms for 10 and 20°C in both hemispheres. The risk to vineyards (and thus the wine industry) is obvious if there is any movement of the upper and lower hemispherical isotherm lines towards their respective poles. In the southern hemisphere the risk to South African and Australian wineries is immediately apparent. If temperatures rise, neither country has the flexibility of relocation. Only South America and New Zealand stand to make any gain in this scenario. Similarly, in the northern hemisphere, there is a risk to the American wine industry but the change may be even greater for the southern European wineries which have the additional challenge of regional identities being strongly tied to wine types.

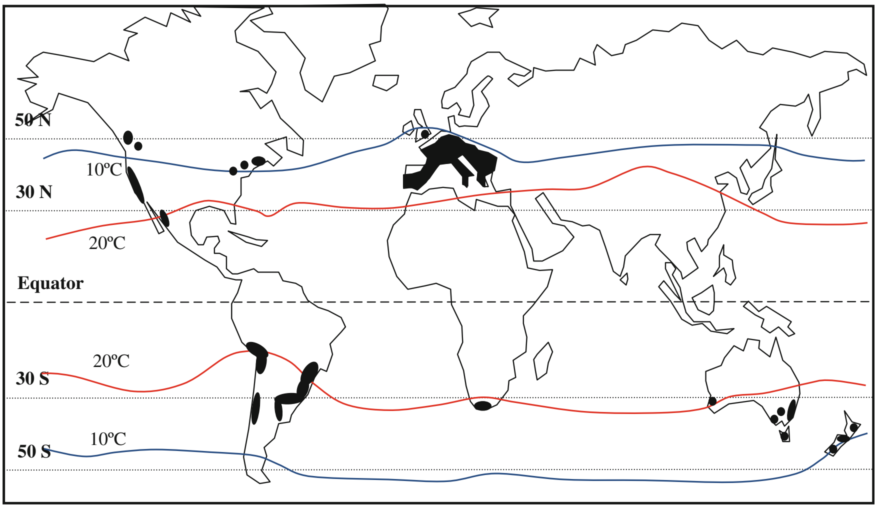

Fig. 1.3 Principle (developed) wine producing regions of the world with present isotherms

However, it is possible that climate change will not neatly push isotherms north or southwards. Climate models by White et al. [14] project that premium wine-growing regions in the US could be reduced from current levels by up to 81%. This severe change is shown in a geographic region that would seem to have the flexibility to replant in response to climate drivers. Figure 1.4 shows a few of the scenarios modelled in the study.

White et al's [14] models show current prime growth areas on the left side of the image labelled a, c, e, and g. The right side of the image shows the corresponding regions after running the climate model. The reduction in available growing regions is stunning.

Of course, as changes in the climate and its impact on the winegrowing regions increases, like any dynamic business, the wine industry will seek to adapt. Whilst climate change may shift the ideal winegrowing locations into new regions, leading to new plantings and wineries, and some wineries already in extreme regions may go out of business, many wineries will have to adapt to the changing conditions by adopting new practices or planting more appropriate varietals. Some wineries are already looking at the long term consequences of climate change. Figures 1.5 and 1.6 depict trials that are being conducted by Torres Winery in Spain. The company has seen a change in the growing conditions in their vineyards and have been quick to realise the consequences on their product. Figure 1.5 shows Xaerlio (a local varietal) being grown under closely monitored conditions. Test batches are subjected to increased ambient temperatures and reduced water and compared with a control batch. In Fig. 1.6 vines in a hermetically sealed greenhouse are supplied with varying concentrations of CO_2 and the plant's growth monitored.

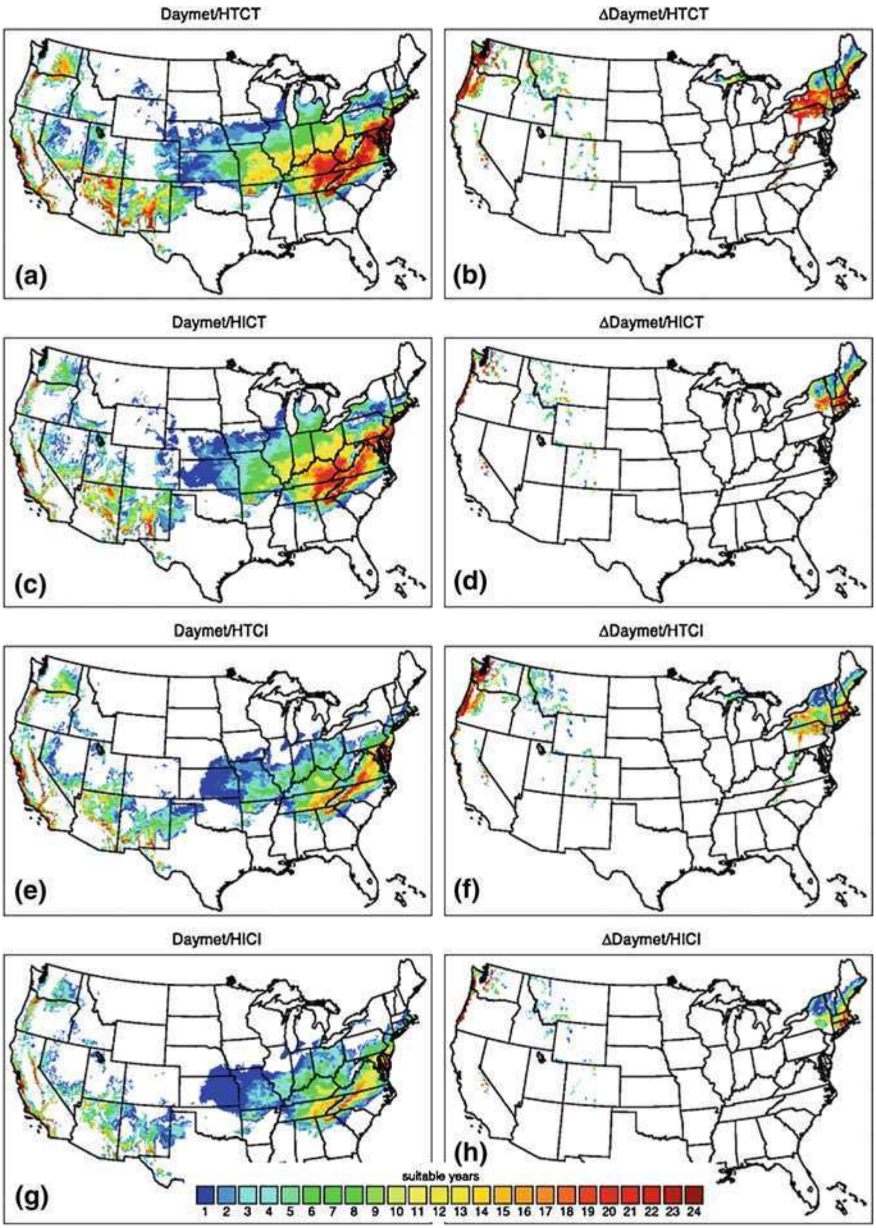

Fig. 1.4 Image of the US map of regions and the changes predicted by modelling (White et al. [14], reproduced by kind permission from PNAS (Copyright 2006, National Academy of Sciences, USA))

Fig. 1.5 Climate change growth trials on different varietals

Fig. 1.6 Impact of CO_2 concentration on vine growth and production

Environmental drivers as detailed above offer a strong argument for moving towards the solar winery model. However, other powerful drivers exist or are developing. Economic drivers are explored in the next section.

1.3 Economic Drivers

Economic drivers for renewable energy (specifically solar renewables) in the winemaking industry could be purely financially driven through rising fuel costs and the downward trend in the cost of renewable technologies. However, for many, these conditions on their own are not enough of a ‘financial carrot’ to induce a significant uptake in solar renewables. In response, many of the (wine producing) nations throughout the world have sought to use financial incentives, either directly or indirectly by legislative action to promote the deployment of solar energy technologies.

1.3.1 Rising Energy/Fuel Costs

Rising energy/fuel costs and increasing instability of fuel markets provide a direct economic incentive to move towards renewable energy sources. Whilst this phenomenon is global, its impact is not uniform, with some regions and industries being affected more than others. Figures 1.7, 1.8 and 1.9 show the relative price increases in natural gas, electricity and gasoline for major wine producing regions of the world (New Zealand, Europe, South Africa and the USA) from 2001 to 2008.

It is clearly evident from these figures that the trend in energy costs for all regions is upwards with significant variation in the rate of increase. The ‘globalised’ wine industry is very much dependent upon fossil fuels and any future rises will have a major impact upon production and transportation costs and ultimately, perhaps the economic sustainability for some producers. Of course, the level of impact will be highly variable depending upon winery location, level of mechanisation and associated production processes and practice.

1.3.2 Decreasing Renewable Technology Costs

Improved technology, manufacturing techniques and increasing economies of scale is driving the cost of (solar) renewable energy technologies lower. Whilst the levelised cost of renewables is still higher than most fossil fuel energy sources the combination of increasing fuel costs and decreasing renewable costs are rapidly driving the two towards equilibrium.

1.3.2.1 Solar Thermal Water Heating

Solar thermal water heating is probably one of the most cost effective forms of renewables (excluding incentives) and through economies of scale the argument for their deployment becomes more appealing. In a study conducted by the

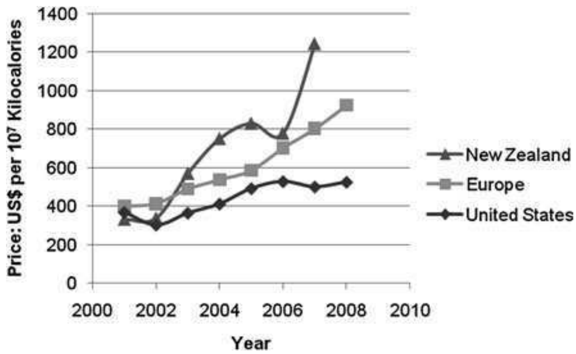

Fig. 1.7 Trends in natural gas prices for 3 wine producing regions (adapted from DOE/EIA [5])

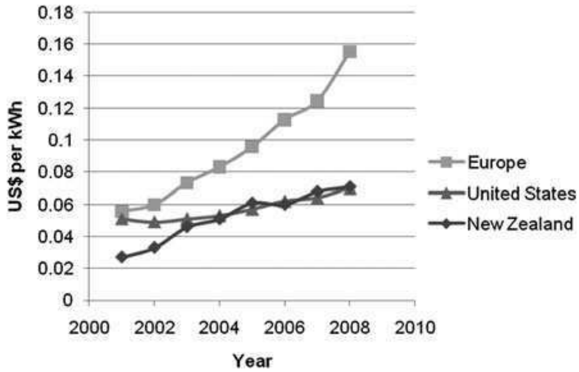

Fig. 1.8 Trends in industrial/commercial electricity prices for 3 wine producing regions (adapted from DOE/EIA [5])

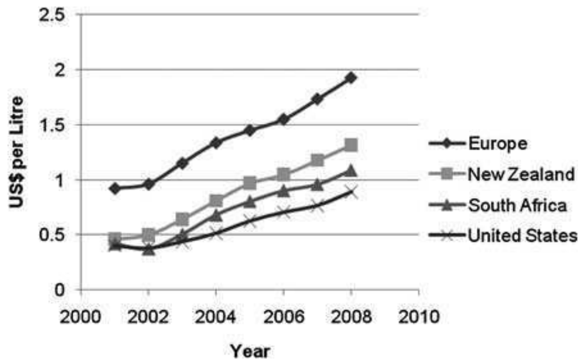

Fig. 1.9 Trends in gasoline prices for 4 wine producing regions (adapted from DOE/EIA [5])

European solar thermal technology platform (ESTTP) [7], the impact that larger scale systems and continued R&D will have on the solar thermal energy costs is shown in adapted form in Fig. 1.10.

Over the past decade investment cost reductions of around 20% have been observed for each 50% increase in the total installed capacity of solar water heaters

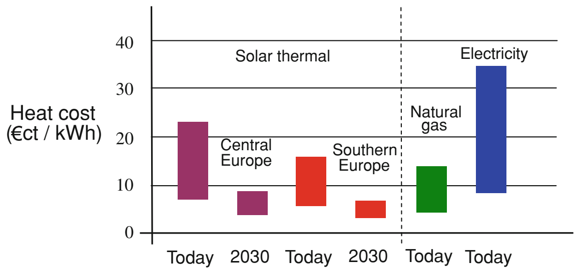

Fig. 1.10 Typical cost range for small/commercial scale DHW production by various sources in Europe (adapted from ESTTP [7])

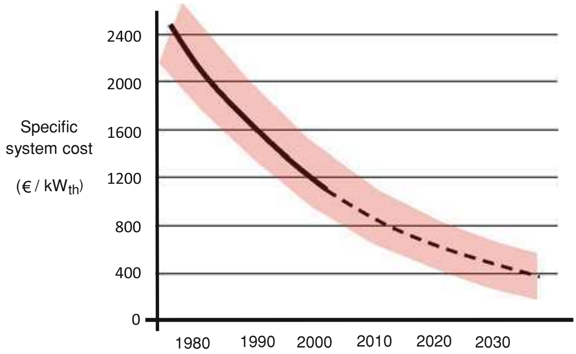

Fig. 1.11 Projected installed cost and capacity for small/commercial scale active solar thermal systems in Europe (adapted from ESTTP [7])

in Europe [7]. Increasing cost reduction potential is also possible in increasing productivity through greater mass production and optimised installation and maintenance works. Figure 1.11 shows the projected installed cost and capacity for small/commercial scale DHW production by active solar thermal systems in Europe.

1.3.2.2 Solar Thermal Power

Solar thermal power is almost cost competitive with traditional forms of power generation, with the possibility of solar thermal generation costs reducing by more than 50% by 2025, according to a study by AT Kearney and the European Solar Thermal Electricity Association [6]. Figure 1.12 illustrates the levelised cost comparison of electricity (€c/kWh) of solar thermal energy versus conventional sources.

1.3.2.3 Photovoltaics

The installed costs of solar photovoltaic systems have declined significantly over the past decade. In study by Wiser et al. [15], the PV module and balance of system (BOS) costs for solar PV systems in the USA from 1998 to 2007 were compiled.

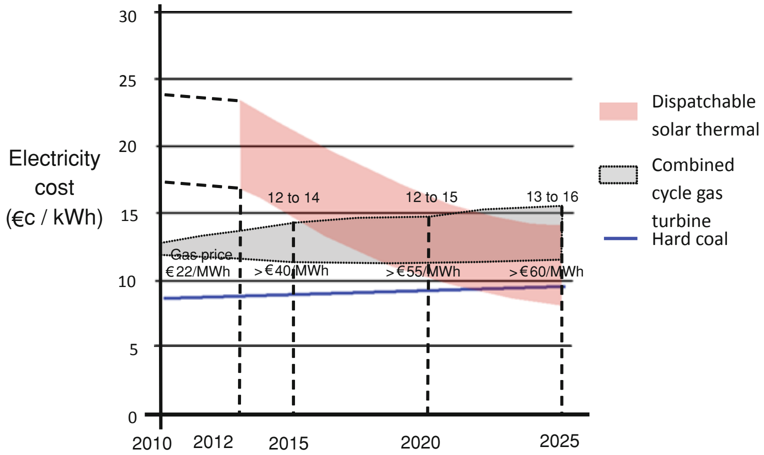

Fig. 1.12 Levelised cost of electricity (€c/kWh) comparison of solar thermal energy versus conventional sources (adapted from European Solar Thermal Electricity Association (ESTELA) [6])

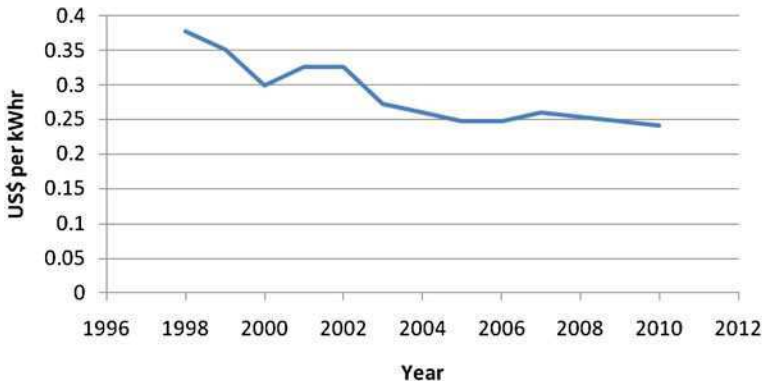

Fig. 1.13 Trends in levelised PV energy costs [15]

Figure 1.13 shows the levelised cost trend of electricity production from a commercial scale grid tied solar PV system (<100 kWp) located in a sunny climate with an annual average of about 5 h of full sun per day.

The trends of increasing energy costs and decreasing renewable energy costs support a strategic investigation of renewable energy project viability and are an important factor in whether a winery will decide upon opting for a solar energy installation. However, a significant economic gap still exists between many solar systems and conventional energy sources, making financial incentives necessary.

The economic viability of a project will depend heavily on government incentives and legislative drivers that have been enacted.

1.4 Political Drivers and Financial Incentives

Political and legislative action has the potential to drive huge changes in the overall carbon intensity of industries and possibly the cost of doing business. The wine industry, as previously mentioned, is estimated to produce only 0.08% of global greenhouse gas emissions. Given this scale, the industry may not be an obvious target for direct legislative action aimed at reducing emissions. However, vineyards and wineries are directly dependent upon several industries with larger carbon footprints such as power generation, transportation, glass production and the fertilizer/pesticide manufacturing industries. In addition, the potential for an across the board carbon tax or a cap and trade system could directly impact the industry.

Currently there is no uniform global agreement on how to legislatively manage carbon emissions. However, three distinct methods or systems have become common including:

- direct reduction in energy consumption through energy efficiency improvements;
- reduction in the carbon intensity of energy consumed through promotion of renewable energy production;
- placing a direct cost on carbon emissions via a carbon tax or carbon trading system.

Energy efficiency improvements and renewable energy production are being driven through by both incentives and legislation while direct carbon emission reduction mechanisms tend to be purely driven by legislation.

1.4.1 Energy Efficiency

Energy efficiency is being promoted through legislation, free market incentives and government based financial incentives. Both direct legislation and free market incentives are embodied in the energy saving certificate markets which promote energy conservation by placing a monetary value on discrete units of energy savings (usually 1 MWh) in the form of energy saving certificates (ESCs) also known as energy efficiency credits (EECs), white certificates or white tags.

Generally, a state or country will devise energy efficiency targets and create a set of policies that define what energy saving measures will count toward the generation of ESCs. The targets and policies set up to reduce energy consumption are often referred to as energy efficiency portfolio standards (EEPS). Globally only

eleven sovereign entities in Europe, the US, and Australia have incorporated ESCs into their EEPS; Denmark, France, Italy, the UK, Connecticut, Pennsylvania, Nevada, Michigan, New South Wales, South Australia, and Victoria [8, 9]. The European Commission has considered legislating energy efficiency measures and targets in the "20-20-20 by 2020" plan. The plan requires that Europe cut greenhouse gas emissions by 20%, produce 20% of energy from renewable sources and increase energy efficiency by 20% by the year 2020. The emissions cut and renewable energy requirements have been incorporated into binding legislation, energy efficiency measures, however, have not.

In the US, nine of the twelve states producing more than 1 million gallons (3.79 million litres) of wine per year have established energy efficiency portfolio standards including; California, Michigan, Missouri, New Jersey, New York, North Carolina, Ohio, Virginia, and Washington [11, 13]. These nine states and twelve others (plus the District of Columbia) will potentially become the compliance and voluntary markets where white tags (ESCs) will be sold. Sterling Planet is currently providing white tag verification and trading services in the US; promoting the creation and trading of white tags.

In addition to the white tag market approaches, energy efficiency is also being promoted through government incentives usually in the form of tax incentives. Tax rebates are country and state specific and are generally targeted to a specific weakness. For example in a country with a large stock of older poorly insulated buildings, tax rebates or other incentives could be provided for weatherisation activities, insulation upgrades and other activities such as window replacement.

1.4.2 Renewable Energy Generation

As mentioned previously, most renewable energy generation is currently more expensive than traditional generation. In general, renewable energy generation is encouraged or required through a number of legislated requirements and/or government funded incentives including:

- net metering;
- feed in tariffs;
- renewable energy portfolio standards and renewable energy credits;
- rebates;
- grants;
- tax credits;
- accelerated depreciation schemes for businesses.

Net metering is a renewable energy policy that uses a meter that records energy flows both into and out of a customer's utility facility. When a facility is using more energy than it is producing, the meter runs "forward" and when the facility is producing more energy than it is consuming, the meter runs "backwards" effectively storing energy credits. Net metering agreements are very common in the US

but are rare elsewhere. Usually, any stored or unused energy credits are rolled over to the next month (although this varies from state to state) and any monthly deficits require payment on the monthly bill. At the end of the year most utilities will buy back any unused energy credits at a rate defined by the power purchase agreement signed between the utility and the customer. Net metering rules vary greatly from state to state so those interested are advised to check with their state utilities commission. Interested parties can find detailed information at the Database of State Incentives for Renewables and Efficiency (DSIRE).

Feed in Tariffs are rare in the US, but are common world-wide. Feed in Tariffs provide an incentive for renewable energy system installation. Unlike net metering, Feed in Tariffs pay grid tied owners for every unit of renewable energy that is produced. The system owner enters into a long term contract generally with their local utility provider. The contract sets a price per unit of energy created that the utility will pay the system owner based on that rate and their production for the life of the contract. Currently, Feed in Tariffs exist in many countries in Europe; some states in Australia; and in California and Hawaii in the US. Tariff availability and rates are very dynamic and therefore will not be quantified here. However, for those interested in initial research of Feed in Tariff availability, the following sources may be useful:

- a good resource for the US is the DSIRE hosted by the Solar Centre at North Carolina State University (www.dsireusa.org);
- for a global status, the website www.solarfeedintariff.net provides a broad overview;
- another site for global information can be viewed at www.globalfeedintariffs.com.

Another mechanism to encourage the production of renewable energy is the renewable energy credit. The green power market promotes renewable energy generation by the generation, tracking, and sales of renewable energy credits (RECs) also known as tradable renewable certificates (TRCs), green certificates or green tags. In most markets RECs and their pricing do not encompass the actual electricity but represent the green attributes of the renewable energy generation as opposed to conventional energy generation. One REC represents the green attributes of the production of 1 MWh of electricity from renewable sources. The money generated by the sale of RECs is intended to spur the creation of new renewable energy generation. RECs are primarily traded in so called compliance markets (though voluntary markets do exist) which are markets in which the government has established a renewable portfolio standard (RPS) which requires that a certain percentage of a utility's power must come from renewable sources [3].

Tradable REC markets exist worldwide. In Europe, Austria, France, Italy, Spain and the UK rank among the 10 EU-27 countries with REC markets [10]. In the US there are 24 states plus the District of Columbia that have implemented Renewable Portfolio Standards including all of the 12 largest wine producing states excluding Ohio [12].

The average retail price of RECs varies from US $1.20 to $20/MWh with RECs produced from solar PV (SolarRECs) demanding a premium [2]. From a winery's perspective, when installing a solar PV system the production from the array will directly lower the power bills based on the electrical production of the array and may even allow sales back to the grid (depending in the net metering rules). These benefits are derived from the generation of electricity (renewable or not). In addition, the winery will be able to sell the RECs generated by the array at the current market price (potentially $0.02–$0.20/kWh). Currently wind and solar PV produce saleable RECs. Solar thermal generation can potentially generate RECs, however, many see solar thermal as an energy saving technology producing white tags not RECs or green tags.

In addition to net metering, Feed in Tariffs and renewable energy credits; there are a multitude of rebates, grants, and tax credits available to increase the uptake of renewable energy technologies. With such an array of systems in place and given the fact that these incentives are constantly in flux, a thorough review of local policy is required in order to determine what is currently available in any given region. Table 1.1 is an attempt to provide some clarity and give a broad overview of current mechanisms in place in many of the potential winegrowing regions of the world.

Prior to investing in a renewable energy generation system, the potential owner must carry out an analysis of the future costs and benefits of the system. These systems have front loaded costs with payback happening gradually over the 20–30 year lifetime of the system. In addition, careful consideration must be given to the sizing of the system and what the type of long term agreements exists (and applicable), such as Feed in Tariff, net metering and/or REC contracts, since some are mutually exclusive. For example, you could choose to take a fixed price for 20 years for net metering and RECs. However, if energy prices from the utility continue climbing it may, in hindsight, become a better option to offset energy consumed within the facility via a net metering agreement. It is probable that as renewable energy technologies become more competitive, incentives such as Feed in Tariffs will be discontinued and, given current trends, it is safe to assume that utility supplied energy prices will continue to climb.

1.4.3 Carbon Pricing Systems

Direct legislative action has also taken the form of carbon pricing systems which are a means to assign a price to carbon emissions that recognizes and accounts for the current externalized costs caused by carbon emissions such as those costs caused by climate change. The two recognized methods for carbon pricing are the carbon tax and carbon emissions trading schemes (also known as cap and trade). A carbon tax places a tax, whose price is determined by a governing body, on fuels containing carbon. Carbon taxes are commonly placed on transportation fuels. A cap and trade system sets an ultimate cap or limit on carbon emissions and then

Table 1.1 Renewable energy policies (adapted from Sawin and Martinot [10])

Country	Feed in Tariff	Renewable portfolio standards	Grants/ Rebates	Investment tax credits	Sales tax/ VAT reduction	Tradable RECs	Energy production payments or tax credits	Net metering	Public loans/ financing	Public competitive bidding
Austria	●		●	●		●			●	
France	●		●	●	●	●			●	●
Germany	●		●	●	●			●	●	
Italy	●	●	●	●	●	●		●	●	
Spain	●		●	●	●	●			●	
UK	●	●	●		●	●			●	
South Africa	●		●		●				●	●
Australia	*	●	●			●			●	
New Zealand			●						●	
US	*	*	●	●	*	*	●	*	*	*
Argentina	●		●	*	●		●		●	●
Chile		●	●	●	●				●	●

Filled circle Implemented at a national level; *Asterisk* Implemented on various state levels

assigns an equivalent number (equivalent to the cap) of carbon permits to emitters. Those who need to emit more carbon than their permits allow must purchase additional permits from others who have been able to reduce emissions. The price of a carbon permit is thus set by the market versus a tax price that is set by a governing body. The largest cap and trade system is the European Union Emissions Trading System which is intended to create the carbon reductions required by the "20-20-20 by 2020" plan. There are other regional carbon reduction initiatives such as the Western Climate Initiative in the western US and Canada. There is also the Regional Greenhouse Gas Initiative which involves the north-eastern US and eastern Canada.

The future for carbon pricing systems in Europe seems the most clear with targets already set for at least a 20% reduction in emissions from 1990 levels. This will continue to impact large emitters of greenhouse gases. In the rest of the world the picture is less clear but it is likely that some means of controlling carbon emissions by legislated price signals will continue to develop.

Environmental, economic and political factors along with individual winery reasons, such as energy/power security or a perceived market image, are powerful drivers in the argument in adopting a sustainable future. Climate change is a reality and will impact the winegrowing industry, fossil fuels are finite and their cost will rise and wine production requires energy, albeit a small percentage on a global context, but nonetheless significant. The stage could not be more set for the solar winery, and as an industry, winemakers should be looking at solar renewable technologies as being just as an important feature of the winery as, say, the grape press or fermentation tank.

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Chapter 2
Introduction to Winemaking

2.1 History of Wine Production

Whilst the creation of wine from spoiled grapes and other fruits was probably known from the earliest days of humankind, it would have been difficult for early hunter-gatherers to control and benefit from this process. It was not until the Neolithic revolution and with it, the discarding of hunter-gatherer or subsistence techniques that humans could successfully cultivate domestic grapes and produce wine. Furthermore, technological developments in pottery were vital in order to ensure that wine could be consistently manufactured, stored and consumed. Recent archaeological discoveries in Armenia provide evidence of large scale organised winemaking activities dating as far back as 4,000 BCE [1]. Other evidence indicates that vitis vinifera, the key winemaking vine, was present in the ecological rich Caucasus region between 6,000 and 4,000 BCE [6].

Whilst small scale indigenous wine production has been documented in regions such as Spain and Tuscany between 4,000 and 3,000 BCE, it was the rise of successive mercantile and conquering civilisations that expanded and spread grape growing and winemaking. Some wine culture spread east but the majority of growth in classic times was westward. Initially it spread into the civilisations of Mesopotamia, Egypt and the Phoenicians, who adopted wine culture and spread winemaking throughout the Eastern Mediterranean into areas such as Crete, Greece and North Africa. The rise of Greek civilisation disseminated the culture of wine further into Sicily and the Italian peninsula. After this, Roman civilisation soon dispersed wine culture throughout western and southern central/eastern Europe and into France, Germany, the Balkans and the Black Sea [11]. Wine became firmly established in Europe due to a variety of social, health and religious reasons, most notably Christianity and the important role wine plays in Eucharist. The silk route and other eastern trade routes spread wine east into parts of India and China and eventually Japan. The Asian expansion of winemaking never reached the same levels as those found in Western Europe and this could probably

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be linked to the dominant role of non-Christian religions in this region, most notably Confucianism, Hinduism and Buddhism.

This expansion to both the east and west across the Eurasian continent was facilitated by similarities in climate; most winemaking was clustered in the 30–50th parallel. Expansion to the north and south of this area was hampered by climates poorly suited to grape growing and winemaking. It was not until the Age of Discovery that wine culture would migrate further from its stronghold in Western Europe. Then, the winemaking countries of Spain and Portugal travelled to the "New World" to expand their territories and took wine with them. Exploration by the Iberian powers was followed by France and wine consuming countries Britain and the Netherlands.

Wine culture found an early home in Central America and then expanded into North America. Whilst Native Americans undoubtedly exploited the fermentation potential of indigenous grape varieties, including vitis rupestris, their efforts would have been similar to those of Palaeolithic and Neolithic Europe. The east coast of North America was unsuitable for grape growing due to the presence of significant vine diseases, such as Phylloxera, Oidium and Peronospora, amongst the non-vinifera grapes; the West Coast of North America between 30 and 50th parallel, however, proved to be compatible. Further expansion took wine to South America in Argentina, Chile and Peru and again wine found a natural home in the 30–50th parallels south of the Equator. The next phase of expansion took wine further into the "New World" to locations such as South Africa, Australia and New Zealand.

Further expansion of winemaking around the world was hampered by climatic and cultural reasons and winemaking remained clustered in the 30–50th parallels (north and south of the Equator) and in predominantly Christian countries. Following modern technological improvements in irrigation and refrigeration advances in viticultural science with respect to canopy management and disease control with wine is now starting to spread north and south from these established areas. This spread can also be attributed to changes in trends in global wine consumption. Currently wine is being produced in such varied places as Brazil, India, China, Thailand, Tanzania, Denmark, Sweden, Baltic States, Eastern Europe, Indonesia and French Polynesia.

2.2 Global Wine Consumption

Patterns of wine consumption all over the world change and evolve continuously. This is in response to a whole range of stimuli including religious, health, socio-economic and cultural reasons. Although there have been some significant localised declines in consumption (total and per capita), most notably in France, Spain and Italy (Fig. 2.1), there have also been many countries where it has increased (Fig. 2.2). In general, world wine consumption has been increasing over the past 10 years. The increase in world consumption is due two distinct trends.

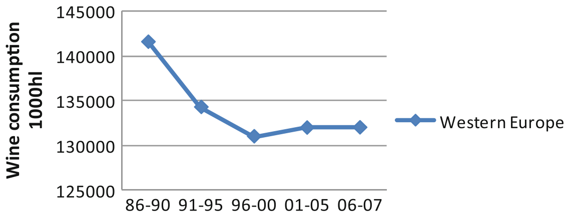


Fig. 2.1 Trends in wine consumption in the western world from 1986–2007 [10]

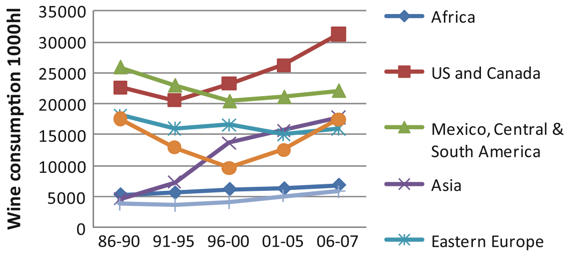


Fig. 2.2 Trends in wine consumption in the rest of the world from 1986–2007 [10]

The first is continued and sustained growth in wine consumption in countries which have a traditionally low base of wine consumption, for various reasons. These countries include the USA and individual countries in Northern and Eastern Europe. The second trend is the emergence of wine consumption in populous countries which previously had an almost non-existent wine culture, most notably India, China and South East Asia. Whilst per capita, consumption in these countries remains low, the sheer size of the population means that even small incremental changes in consumption cause large increases in volumes of consumption. This increase in consumption is often anecdotally linked to improving GDP and the rise of a new affluent middle class adopting elements of Western culture and consumerism.

2.3 Global Wine Production

With global wine consumption generally increasing and wine culture spreading to more diverse areas, there has been a spread of vineyards around the world. Traditionally, vineyards have served the "Old World" of Western Europe and have been primarily located in France, Italy, Spain and, to a lesser extent, Portugal, Greece, Balkans and Black sea regions, servicing local demand. As other benign viticulture climates in the "New World" have been discovered within the 30–50th parallels, these have been developed, partly to supply local consumption, but more often to service export markets.

As global consumption and demand has increased in the twentieth and twentyfirst centuries, wine has spread from these "Old World" and "New World" regions into even more diverse locations. The "Old World" wine regions exploited

Fig. 2.3 Windmill and 'smudge' pot frost protection in Northern California

the natural climate of the Mediterranean basin and Near East. This warm and dry summer and autumn/fall climate, generally allows a good yield of ripe and disease-free fruit. These grape growing conditions make winemaking tasks simpler and provide the potential to make good quality wine. Moving away from the Mediterranean basin, grape growing becomes more difficult.

As grape growing and winemaking occurs further away from the equator, weather conditions become more unpredictable and grapes often suffer from a lack of sunshine, insufficient heat and excess rain, hail and frost. To offset this, site selection and viticultural techniques become more important. This often requires a large investment in frost protection, canopy management and disease control. As these wineries are often processing later ripening fruit, they are more affected by late autumn/fall and early winter temperatures and because of this, there can be significant extra requirements for heating grapes, juice, wines and facilities (Fig. 2.3).

If grape growing and winemaking occurs closer to the equator, weather conditions become more predictable. These regions usually have an abundance of sunshine and high temperatures, but will often lack significant rainfall for the growing season. To ensure good vine growth and suitable ripening of the grapes, large scale irrigation is often required. Here grape ripening is usually accelerated and often wineries will be processing fruit during the hot late summer, early autumn weather. This means significant refrigeration is required to cool grapes, fermentation and wine storage.

2.4 Wine Style

Winemaking is simply the conversion of grape juice and must into an alcoholic beverage through a series of biological and chemical processes. However, if left unchecked or uncontrolled, these processes usually result in wines containing high

ethanal (acetyl aldehyde), ethyl acetate and acetic acid (collectively known as VA) and other spoilage chemicals and is not suitable for consumption. It is therefore the winemaker's role to engage with the process to ensure that the wine is produced correctly and in the desired style.

As befits a beverage with a long history and a wide geographical spread and consumer appeal, there are a myriad of wine styles in production. The final choice of winemaking direction is very much based upon which varieties are available, the climate and geography they are grown in, winery infrastructure available, market requirements, economic consideration and personal winemaking philosophies. Wine styles can be categorised in many ways. These include:

- Table wines: Wines made with low sugar levels (usually referred to as dry styles)
- Sparkling wines: Wines which contain carbonation
- Dessert wines: Wines which contain residual sugar, including *Botrytis* and ice-wine styles
- Fortified wines: Wines that have been made with the addition of fortifying brandy or spirit. These can be further classified into sweet wine styles and dry wine styles
- Distillation wines: Wines that have been made in order to be distilled into spirit

Further to this, wines can also generally be classified by colour:

- White: Wines made with minimal influence from the skins, predominantly from white grapes i.e. Chardonnay, Albarino and Pinot Grigio
- Blush/Rose: Wines made with some minor influence of the skins. These are predominantly made from red/black grapes such as Pinot Noir, Grenache/Granacha, Zinfandel/Primitivo
- Red: Wines made with significant influence of the skins, predominantly from red/black grapes such as Shiraz/Syrah, Tempranillo and Nebbiolo

Whilst most wines conform to these classifications, there are exceptions to these, such as white wines made with skin contact or white wine styles made from black grapes with minimal skin contact.

Some wine styles, however, are unique and do not conform to the simple categories above. These include "new" styles such as Beaujolais Nouveau or the Italian style Novello which include an element of carbonic macerations (a yeast free internal berry fermentation); wines made from heat treated grapes or grape juice such as Mosto Cotto or thermo-vinified wines; wines made from dehydrated grapes such as Passito and Amarone and finally, flavoured or aromatised wines including Vermouth or Marsala.

The main components of grapes are listed in the following section. The level of components found in each grape will be dependent upon the grape variety, vineyard and the local environment (terroir) and maturity at the point of picking. The levels of these key components will play a role in determining how likely a winemaker is able to produce wine in the required style.

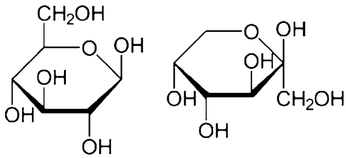


Fig. 2.4 Molecular diagram of glucose (*left*) and fructose (*right*)

2.5 Grape Components

Grape berries consist of a variety of chemicals which will influence wine style, wine quality and winemaking decisions. The key compounds are listed below in order of most common to least common:

Water: Grapes primarily consist of water, primarily held in the berry pulp.

Sugar: The second most abundant compound in grapes and found concentrated in the pulp. The sugars in grapes are predominantly glucose and fructose and will make up 15–30% plus of the total juice mass. As glucose and fructose are utilised in fermentation, the levels found in the grape will dictate the final alcohol level available in wine. At sugar levels above 25%, fermentation can become difficult and there is a significant chance that fermentation will halt before all sugars are consumed. At sugar levels of >30%, complete fermentation is nearly impossible and this wine will often be very sweet and considered to be in a dessert style (Fig. 2.4).

Acids: The next most abundant (0.5–1.5% of juice) grape chemical is tartaric and malic acid, located in the berry pulp. Present in high levels in unripe grapes, the acid levels decline as the grapes ripen. With warm temperatures, malic acid can degrade significantly and leave the berries low in acid with a high corresponding pH. Acid levels play an important role in microbial stability, oxidative stability, wine colour, wine flavour and balance (Fig. 2.5).

Phenolic and polyphenol compounds: A small but significant family of chemicals found in grapes. These compounds all contain one or more phenol (aromatic alcohol) group. They can be quite diverse, ranging from simple non-flavonoids such as Gallic and Cinnamic acid, to more complicated flavonoid groups such as Quercetin, Epicatechin and Malvidin. These flavonoid and non-flavonoid compounds are highly reactive and will often react with other phenolic compounds and polymerise into larger macromolecules. As a group, the phenolic compounds are responsible for red, purple, yellow and brown colours, astringency, bitterness and anti-oxidant capacity in wine. While simple non-flavonoids are found in the grape pulp, the larger more complex flavonoids are mainly found in skins and seeds. Other non-flavonoids may also be found in oak used in cooperage. They make up to 0.5% of the mass of juice (Figs. 2.6, 2.7, 2.8, 2.9).

Aroma and flavour compounds: Located predominantly in berry skins and pulp, these are diverse groups of sensory active compounds. They include chemical families such as monoterpenes (twin isoprene units) that provide floral/grape-like flavour in Muscat grapes; thiols (compounds containing a sulphur-hydral group) that provide cat urine, passion fruit and grapefruit aroma in Sauvignon Blanc

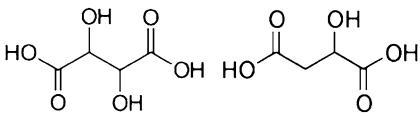


Fig. 2.5 Molecular diagram of tartaric acid (*left*) and malic acid (*right*)

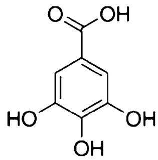


Fig. 2.6 Molecular diagram of non-flavonoids found in oak like Gallic acid

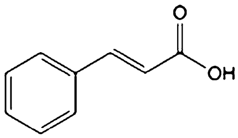


Fig. 2.7 Molecular diagram of non-flavonoids found in grape berry pulp like Cinnamic acid

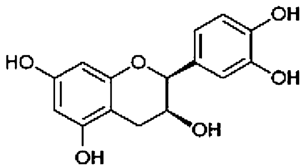


Fig. 2.8 Molecular diagram of flavonoids found in seeds like (+) Epicatechin

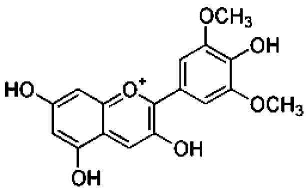


Fig. 2.9 Molecular diagram of flavonoids found in skins such as the anthocyanin Malvidin

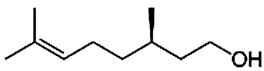


Fig. 2.10 Molecular diagram of terpene aromas such as Citronellol

grapes; and pyrazines (nitrogenated hetrocycles) that provide vegetative aroma in Cabernet Sauvignon and Sauvignon Blanc [8] (Figs. 2.10, 2.11, 2.12).

Nitrogen compounds: These include ammonium ions, amino acids, peptides, polypeptides and proteins and can be found in pulp, skins and seeds. These compounds are a vital source of nitrogen for yeast development (Fig. 2.13).

Minerals and inorganic compounds: Grape juice contains many minerals; most notable are metal cations such as potassium, sodium and calcium. They are found in the pulp and skins.

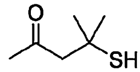


Fig. 2.11 Molecular diagram of thiol aromas such as 4 mercapto-4metylpentan-2-one (4MMP)

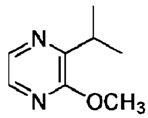
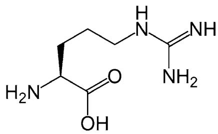


Fig. 2.12 Molecular diagram of pyrazine aromas such as 3 isopopyl-2methoxypyrazine (IPMP)



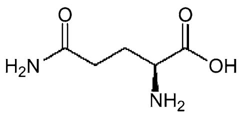


Fig. 2.13 Molecular diagram of amino acids such as Arginine (*left*) and Glutamine (*right*)

2.6 Overview of Winemaking

Grapes are harvested when they are most suitable for producing the desired style. For example, full-bodied table wine styles, dessert wines and fortified wines generally require riper grapes with well-developed flavour, colour and tannins, as well as high levels of sugar. More medium bodied styles of table wine are often picked earlier and retain more acidity at the expense of some sugar and flavour development. Lighter table wines, sparkling wines and distillation wines are picked at a fairly early stage to ensure high levels of acidity and modest alcohol. It is still important, however, that they should avoid excessive unripe flavours (Fig. 2.14).

Harvest methods will be dictated by economics, topography, logistics and wine style. As machine harvesting can damage the fruit, it can lead to excessive colour, flavour and polyphenol pick up. Whilst this is acceptable in many styles of wine, it will not be for light bodied white table wines and sparkling wines. Once harvested the aim of grape processing is to take the grapes and prepare them for fermentation. In white and rose wine styles this will be achieved with minimal contact between the skins and the juice. In red wines styles the juice and skins will be left in contact throughout the duration of the ferment.

Wineries focused on high quality production may sort the fruit prior to processing. The aim of this is to remove unripe, diseased or damaged fruit. In addition, any material other than the grapes (MOG) can also be removed at this time. To improve the pressing process, grapes are often, but not always, crushed prior to loading into the press. This will allow juice to separate from the grapes more easily and provide a higher yield. It must be noted, however, that crushing the fruit will also increase the release of skin/seed compounds including flavour, aroma and phenolic compounds. In some wine styles (full-bodied white and red wines) the crushed grapes and juice (must) may be allowed to macerate, that is: the fruit to be crushed and left to sit in order to increase extraction of these skin compounds.

Fig. 2.14 Cabernet Sauvignon grapes prior to harvesting

Fruit is also often de-stemmed, this is to remove the stalks which can often add excessively bitter and herbaceous characters to the wine.

For red wine styles, fermentation occurs while the juice is in contact with the skins. The juice will start to ferment due to the action of indigenous or inoculated yeast and will continue for a substantial period of time. During this time the fermenting wine will separate into a semi-dry mass of skins (known as the cap), floating on top of the wine below. Throughout the fermentation the wine will be periodically brought back in contact with the cap to ensure the successful extraction of colour, flavour and tannin from the grape skins. This process of "cap management" will depend upon winery resources and the ultimate wine style desired for the wine. During this stage, ferment temperatures will be controlled to minimise problems and help develop flavour, colour and tannin as dictated by the wine style. Other interventions such as nutrition, acid adjustment and aeration may also be undertaken to ensure a successful fermentation. After red fermentation the wine may be allowed to remain in contact with the skins for an extended maceration and allow further development of wine character. Once the desired levels of colour, tannin and flavour are achieved, the tanks will be drained of wine and the skins will be pressed. The wine from pressing (press wine) will either be incorporated into the drained wine (free-run wine) or it may be treated, segregated or discarded depending upon relative wine quality and delivery of wine style.

All white and rose styles will be put through a pressing process, to extract juice from the mass of grape skins, seeds and stalks. This is done through physical pressures being applied to the grape mass as it is held against slotted screens. The juice will pass through the screens for collection and further processing. As the application of pressure further damages the skins, it will liberate additional phenolic compound responsible for astringency, bitterness and colour. Therefore, as the pressing cycle process continues, the juice quality will change and will generally become less appropriate for some wine styles.

After pressing, the resulting juice is a mixture that is high in suspended solids and other particulates. These particulates include skins, seed and stalk fragments,

colloidal suspensions of pectins, agglomerated macro-molecules (proteins/polyphenols) and microbes (yeast and bacteria). Following most common winery processing options (the exception being slow and gentle whole berry processing), the level of solids entrained in juice is excessive and will lead to poor quality wine if fermentation was to be carried out straight away. Instead the wine will often undergo clarification, to reduce the level of solids prior to the fermentation of wine. At this stage any sensory defects may be addressed by the addition of fining agents.

Once the desired clarification is achieved, the juice will be prepared to undergo an alcoholic fermentation with yeast. Sometimes juices will have excess or deficiencies in sugar, acid and nutrition which may require correction to allow achievement of the desired style. These adjustments may be undertaken at this stage or later during the course of the fermentation. After any pre-ferment adjustments the wine is ready for the yeast to become active. This can occur with yeast indigenous to the winery and vineyard or through the addition of an inoculum of yeast selected by the winemaker. To minimise the risk of a slow and difficult start, juices are often warmed to 18–20°C to ensure the yeast has optimal growth conditions. The ferment will be strictly monitored and the winemaker may make interventions regarding temperature, nutrition and levels of aeration as required to achieve the desired wine style. Fermentation can be stopped early to retain sugar (dessert and off-dry styles) or allowed to go to completion (dry styles).

Post fermentation, the wine will contain significant levels of yeast, yeast debris, and other solids. This lees material may have significant impact upon the wine and wine style if left in contact with wine. The lees will release beneficial compounds such as mannoproteins, amino acids, aromas and flavours. This can enhance wine stability and character while minimising the effects of oxygen uptake and oxidation. The lees will also contain material which will act as a source of nutrition for other wine microbes. This can be beneficial or detrimental depending on whether these microbes are of benefit, such as *Oenococcus oeni* responsible for malolactic fermentation, or detriment, such as the spoilage micro-organisms *Brettanomyces*, mycodermic yeast and acetobacter.

The wine may undergo malolactic fermentation (MLF), if so desired and if beneficial to the final wine style, at this time. MLF is carried out by lactic acid bacteria and results in significant changes to wine chemistry and final style. The acidity levels of the wine are reduced and significant sensory changes may occur such as the formation of butter/savoury notes (due to diacetyl and butan 2,3 diol). To improve the chances of a successful MLF, the winemaker will ensure that acidity levels, nutrition and temperature will be controlled so that the environment is favourable to a quick and problem-free MLF. Sometimes the wine conditions are considered too inhibitory due to low pH, excessive alcohol or cold temperature and in these situations some winemakers will co-inoculate with MLF bacteria during alcoholic fermentation. This will allow MLF to initiate and proceed when conditions are more favourable.

Following on from alcoholic fermentation and MLF, if required, the wine will undergo a period of maturation. The aim of maturation is to allow the wine

chemistry to proceed until this brings about the required physical and sensory changes. This maturation can occur in tank or barrel and in the presence or absence of fermentation lees. Beneficial reactions during this time include polymerisation of polyphenols, stabilisation of wine colour and development of favourable sensory characters. During this stage the wine may benefit from some contact with controlled amounts of oxygen. This oxygen may come from periodic racking and wine transfers, oxygen transfer into oak barrels or through the modern process of micro-oxygenation (MO*x*). If the wine is matured in contact with oak (via oak barrels or the addition of oak chips and staves) there will also be the possible accumulation of oak derived components such as vanillin, furfural, cis and trans octalactone as well as oak-derived tannin. Wine stored in barrels will also be subjected to the evaporation of water and alcohol through the oak staves, depending upon storage temperature and humidity.

Following maturation, wine may require further stabilisation. Wines post fermentation may contain excessive potassium bitartrate, calcium tartrate and heat labile proteins. If the unstable wines are packaged, these unstable components may precipitate, reducing the wine's appeal to consumers. Consequently, the winemaker will often seek to treat wines and ensure that they will not undergo further chemical changes in bottle. Potassium bitartrate or cold instability is often treated through the inducement of the instability. For example, if the wine is subjected to significant cold temperatures and/or the addition of cream of tartar seed crystals, the excess bitartrate can be forced to precipitate while the wine remains in the wine. This renders the wine cold stable and makes it unlikely to develop tartrate deposits once packaged. Alternatively additives such as CMC, yeast derived mannoportiens, gum Arabic or metatartaric acid can be added to the wine to restrict crystal growth. This can delay or completely inhibit bitartrate crystal formation and make the wine stable. In the case of heat labile protein instability or heat instability, the wine may be treated to remove problem proteins (addition of bentonite and other additives). Once the proteins are removed, they are no longer available to form haze later if the wine undergoes unexpected temperature shocks, whether in storage, in transportation or in the consumer's home.

Consumers of most modern wine styles require wines to be limpid (that is, have brilliant clarity) and free from the risk of microbial spoilage. To achieve this, wine will need to be clarified prior to packaging. The degree of clarification will be determined by wine maturity, consumer expectation and final desired wine style. Many wines will require minimal clarification and so the wine will be screened to remove any large extraneous debris. However, styles that are early into bottle and wines at risk of microbial spoilage (those retaining micro-organism metabolites such as sugar and malic acid) often require extensive clarification. Clarification can be achieved through a variety of means including settling, centrifugation, earth filtration, depth filtration, membrane filtration and cross-flow filtration. Wineries will choose a combination of methods, depending upon existing equipment and filtration outcome required, in order to successfully produce the nominated wine style. Fortified and dry table wines generally require less intervention than sweet wine styles.

Once the wines are at the desired clarity and sensory state, the wine is ready to be packaged. It will be taken from the winery to a packaging facility, either on-site, at a remote location or a mobile bottling line where it is filled into discrete containers. Whilst traditionally this has meant glass bottle and cork stopper, today's winemakers have many options including PET bottles, aluminium cans, lined cardboard (Tetra Pak®) or soft foil pouches. These containers will either contain integral seals or possible additional seals made from natural cork, technical cork which is generally agglomerated cork (DIAM®, Twintop®), roll on tamper evident or ROTE (Stelvin® and other brands of aluminium screw cap), plastic stopper (Zork®, Nomacorc®) or glass closures (Vino-Lok®).

Sparkling wines deviate from the process described above as they will require some carbonation when packaged. To achieve this final carbonation three process may be used:

- Retention of CO_2 during initial alcoholic fermentation
- Retention of CO_2 during a second alcoholic fermentation
- Injection and dissolution of carbon dioxide into wine (carbonation)

Carbonation will occur to finished wine just prior to packaging and involves carbon injection into the wine followed by filling under pressurised conditions. This method is considered to be low quality and is reserved for low price wines. This may be achieved by bottling and retaining the dissolved carbon dioxide from fermentation. This can be achieved by packaging the wine prior to completion of primary fermentation (méthode ancestrale or rurale) or by carrying out the alcoholic fermentation in pressurised tanks. This method is notably found in Asti style wine.

The majority of sparkling wine is produced through a secondary fermentation process. The wines are generally made as a standard table wine and undergo normal alcoholic fermentation, MLF if required, and are then blended, stabilised and clarified. At this point they are considered to be base wines and ready to undergo second alcoholic fermentation. This secondary fermentation will occur in a confined volume in either a pressurised tank (known as Charmat or tank fermentation) or with individual wine bottles (either méthode traditionale or the transfer method). To achieve a second alcoholic fermentation additional sugar, nutrition and yeast will be added to the base wines in a process known as tirage. Fermentation will then occur and any carbon dioxide that is produced will be retained in solution. After the second alcoholic fermentation, the wines are generally allowed to remain in contact with the lees. The autolysis process will then occur and is considered to add sensory characteristic, particularly beneficial to sparkling wines. Once the desired level of autolysis has been achieved the wine is clarified in preparation for final bottling. For the Charmat and transfer wine styles, this will occur through filtration. In the case of méthode traditionale wines, the bottles will be inverted and agitated (riddling) and then opened to expel and remove the yeast debris (disgorging). Once the wine has been clarified it will have final adjustments made, known as dosage, which includes the addition of sugar, sweet wine, preservatives, alcohol, etc. and then sealed.

2.6.1 Alcoholic Fermentation

At the heart of almost all winemaking is the process of yeast fermentation. This is the biological conversion of grape sugar (glucose and fructose) to ethanol.

The fermentation process had been known about since ancient times and exploited by people in order to convert any liquid containing sugars into alcoholic beverages. Even though it was exploited for thousands of years, however, until recently it was comparatively poorly understood in that the production of alcohol in the final beverage was often considered to be spontaneous generation. This process was studied by chemists and was considered to be a purely chemically catalysed reaction [2]. It was not until the pioneering microscopy work of Anton van Leeuwenhoek [6] that some progress began to be made. This was followed by the observations and experimentation of Charles Cagniard-Latour, Friedrich Kützing and Theodor Schwan [2] culminating in the ground-breaking studies by Louis Pasteur, when finally the process of alcoholic fermentation of sugar by yeast process was well documented and accepted [6]. Pasteur went on to study the process in great detail and identify the anaerobic nature of the process.

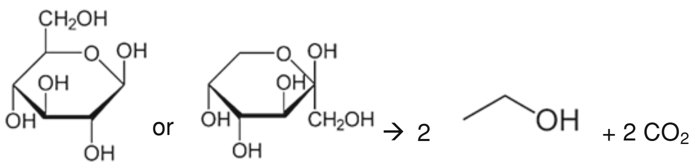
For successful fermentation of sugar the yeasts must be able to metabolise sugar anaerobically. The basic theoretical reaction of anaerobic fermentation is often given as (Fig. 2.15):

Of this, approximately 136 kJ/mol of sugar energy is used in yeast functions, such as cell maintenance including uptake of nutrition and expulsion of waste material, as well as growth requirements such as amino acid synthesis, etc. The remaining energy of 100 kJ/mol produces waste heat and mechanical energy which primarily results in the formation of carbon dioxide bubbles [8]. Therefore grapes with 180 g/l glucose and fructose will theoretically produce 92 g ethanol (129 ml pure EtOH), and 88 g carbon dioxide (74 L at 1 bar and 20°C) and 100 kJ of heat and energy.

Through observations, however, it has been discovered that this theoretical reaction is not achieved in real fermentation systems. Yeast has other by-products of fermentation including glycerol, fatty acids and higher alcohols, which often contribute both positive and negative sensory properties. Finally some sugars are unavailable for fermentation and a proportion of the sugar carbon will be used in other biological synthesis reactions that produce polysaccharides, polypeptides, proteins, etc. [8]. Usually 5–10% of all grape sugar is converted into fermentation by-products and is not converted into ethanol and carbon dioxide.

With advances in microbiology and biochemistry the idea of this simple sugar to ethanol reaction has been investigated and replaced with a series of complicated metabolic pathways which include glycolysis, anaerobic fermentation (pyruvate decarboxylation and ethanal/acetaldehyde dehydrogenation), aerobic respiration (Tricarboxylic acid/Krebs cycle), glyceropyruvic fermentation and others that occur within the micro-organism [13] (Fig. 2.16).

These metabolic processes are of key interest to the winemaker as they influence both wine style and quality, as outlined in Fig. 2.17. If yeast could be



$$C_6H_{12}O_6 \text{ (yeast)} \rightarrow 2\,CH_3CH_2OH + 2\,CO_2 + 236 \text{ kJ/mole energy}$$

Glucose or Fructose — Ethanol — Carbon dioxide

Fig. 2.15 Theoretical reaction of anaerobic fermentation

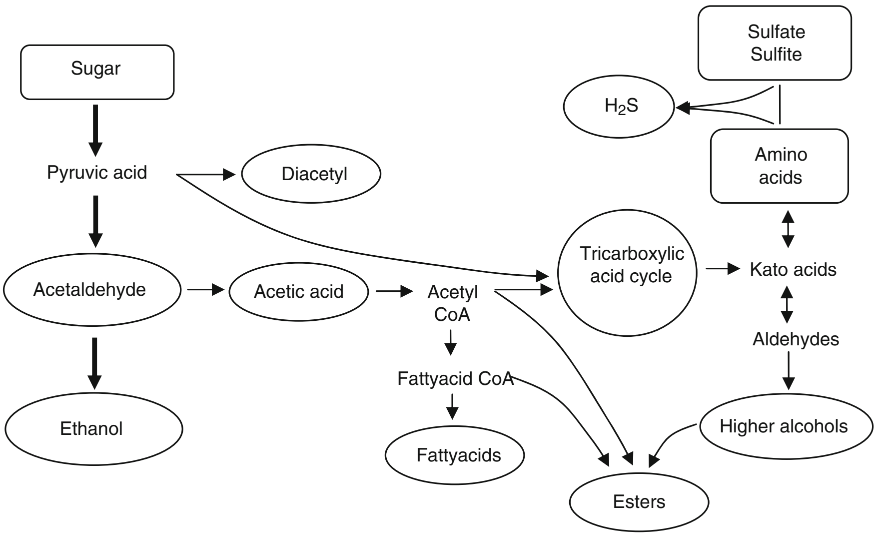


Fig. 2.16 The process of fermentation (adapted from Bell and Henschke [3])

restricted to pure glycolysis and fermentation, the resultant wine will have the highest proportion of ethanol and limited sensory active compounds (higher alcohols, esters, aldehydes etc.). The more sugar that is diverted away from alcohol production, the more sensory active compounds are formed which either can be beneficial or detrimental to the final wine. This metabolic process is influenced by the winemaker in two key ways; yeast selection and temperature control.

The most important winemaking yeasts are *Saccharomyces cerevisiae* (the name is derived from the Latin for sugar loving beer yeast), which is well adapted to making wine. It is an anaerobic yeast with a high degree of sugar and alcohol tolerance. It is one of the few micro-organisms which are adapted to the alcohol levels of normal wines. Over the years, strains of *S. cerevisiae* have been selected for winery environments for their ability to tolerate a grape juice/must environment while producing the requisite levels of ethanol. They have been

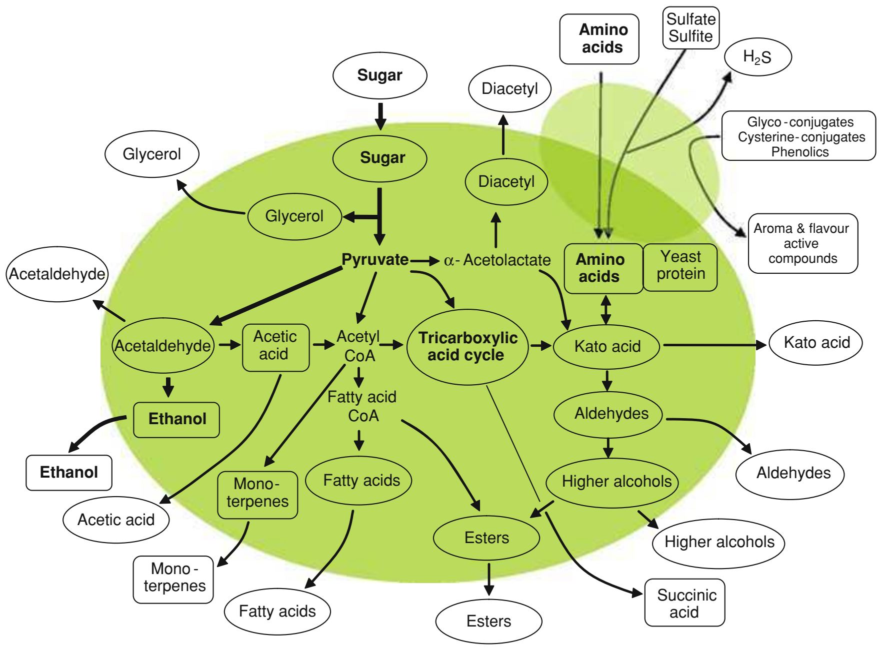


Fig. 2.17 Overview of yeast metabolism (adapted from Swiegers et al. [14])

further refined to favour ethanol production and limit the by-product production of spoilage compounds, such as acetic acid and ethyl acetate, collectively referred to as volatile acidity or VA [15]. However, while *S.cerevisiae* are most suited to winemaking, there are other yeasts, such as *Kloeckera apiculata, Hanseniaspora uvarum, Metschnikowia pulcherrima, Candida* var, *Pichia* var [13] which also compete in the juice/must and wine environments. These non-*S.cerevisiae* yeasts tend to lack ethanol tolerances or be comparatively slower growing and so are unable to carryout successful fermentation. When they are present in sufficient numbers, however, they can significantly impact wine character.

For some winemakers, and certain wine styles, the more reliable and predictable results of *S.cerevisiae* fermentation are favoured. In these situations, the juices or must are usually inoculated with a high numbers of cells of a single selected strain of *S.cerevisiae* yeast. These *S.cerevisiae* yeasts, being well adapted to the grape juice environment and added at high yeast numbers, will generally dominate the alcoholic fermentation. The successful addition of *S.cerevisiae* starter yeast will soon make the juice environment anaerobic, consume vital nutrients and produce ethanol and other toxins which will suppress any other non-*S.cerevisiae* yeast species present.

Other winemakers will choose to favour the indigenous micro-flora present in the vineyard and winery. This will allow many differing genus, species and strains of yeast to ferment co-currently. This style of fermentation tends to have a

complex growth pattern, with competition between differing yeast growing at different rates. The large varieties of yeasts present tends to produce more and varied sensory by-products and will often produce wine styles with a myriad of flavours, which is usually described as complexity in the wine tasting lexicon. In these non-inoculated ferments, as the ethanol levels increase, the less ethanol tolerant species soon become non-viable and this leaves the most ethanol tolerant species such as *S.cerevisiae* yeast free to complete fermentation. Whilst these styles of ferments can produce beneficial effects in the final wine, they can also lead to poor sensory characters and slow or incomplete fermentations.

Finally, some winemakers adopt a more hybrid approach and will inoculate with several selected strains of *S.cerevisiae* or a mixture of *S.cerevisiae* and non-*S.cerevisiae* strains, for example using *Torulaspora delbrueckii* and *Kluyveromyces thermotolerans*. Some winemakers will allow a non-inoculated fermentation to start and then after some fermentation has occurred via the indigenous yeast, they will carryout an inoculation with a strong culture of *S.cerevisiae* yeast, to take over and produce a more reliable end to fermentation and less risk of defect or non-completion.

The other significant way to influence the outcome of fermentation is through temperature control. As a ferment progresses, the yeast generates waste heat which is absorbed by the fermenting wine. This results in increasing temperatures which will significantly influence yeast activity and metabolism. The yeast response to temperatures is complex and can result in significant changes to fermentation rate, nutrition use, bio-mass production and the metabolic reactions which produce by-product chemicals. For example, fermentation conducted at higher temperatures often favours glycerol production [13]. It can be postulated that this might occur because glyceropyruvic fermentation releases less energy into the surrounding liquid, limiting further temperature increases, which is beneficial to maintaining yeast viability. However, the downside to this increased glyceropyruvic formation is the production of increased levels of glycerol and volatile acidity. Through manipulation of temperature we can also affect thiol release [7], ester formation [9] and many other sensory compounds. Finally, extremes in fermentation temperature or rapid changes in fermentation can result in significant disruption to yeast cell function and cause fermentations to slow or stop [16]. *S.cerevisiae* yeast tolerates a range of temperatures (10–35°C), however this temperature tolerance is reduced (<30°C) when there is a high level of ethanol present [13]. Therefore, careful control of fermentation temperature through refrigeration can allow winemakers to influence the quality of fermentation. Failure to adequately control ferment temperature can result in poor fermentation leading to a rise in sensory defects as well as incomplete fermentation (characterised by significant residual sugar in the wine).

After yeast selection and temperature, fermentation will also be effected by numerous other factors, notably nutrition, aeration, pH levels and presence of growth factors or inhibitors. All these can and will affect final wine quality and modern winemakers often choose to exercise control over these factors by winemaking action and use of additives and processing aids.

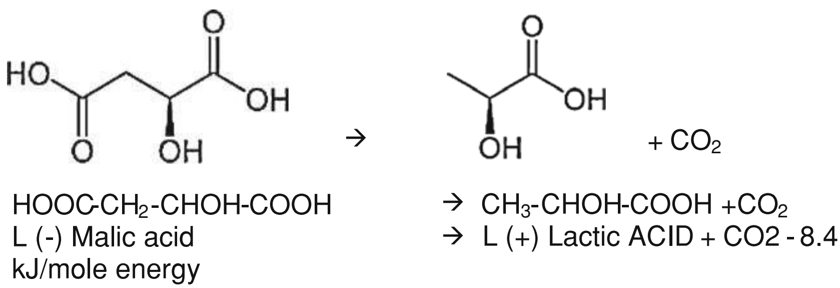


Fig. 2.18 Malolactic fermentation [8]

2.6.2 Malolactic Fermentation

The second major biochemical change in wines occurs through the process of malolactic fermentation (MLF). Whilst it usually occurs after primary alcoholic fermentation, it can also occur co-currently with alcoholic fermentation or even precede it. It is a metabolism of malic acid to lactic acid carried out by a family of lactic acid bacteria (LAB) and in particular *Oenococcus oeni*. The MLF process can be summarised as shown in Fig. 2.18

It should be noted that while it is generally referred to as a fermentation process, it does not adhere to the biochemical classification of fermentation and is best considered to be an enzymatic transformation [4]. In the initial growth stages LAB will consume sugars and produce lactic acid via homofermentative or hetrofermentative pathways [13], only swapping to malic acid degradation after growth is complete. This process is not as dramatic as alcohol fermentation, as the bacterial biomass is small and the amounts of malic consumed are significantly less (3–5 g/l) than the sugar levels (160–300 g/l) present in juice.

The growth of LAB and subsequent metabolic process such as MLF can have significant impact upon wine. The most notable change occurs when malic acid is consumed and lactic acid is produced. This has a significant impact upon wine pH and acidity, as malic acid is a diprotic acid that is stronger than the monoprotic lactic acid. As the malic acid is consumed the acid levels in the wine will decrease and the pH increase.

Similar to yeast there are many other biochemical pathways active within the bacteria. These include primary growth of LAB from sugar consumption, which results in the accumulation of lactic acid, carbon dioxide, ethanol and acetic acid. Finally there are other metabolisms occurring within the bacteria which lead to production of various sensory attributes including acetic acid and ethyl acetate, which are vinegary and solvent-like, to compounds like diacetyl and butan 2,3 diol, which are buttery. Many of the metabolic compounds produced by LAB are summarised and shown in Fig. 2.19.

Whilst alcoholic fermentation is at the heart of winemaking, LAB growth and MLF is optional and not always desirable. For many wine styles it will be

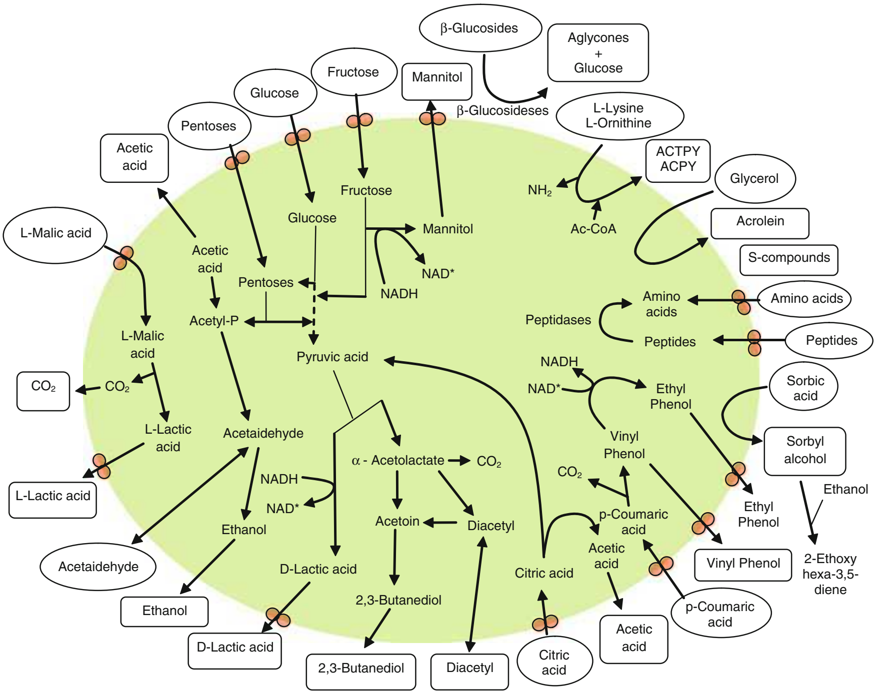


Fig. 2.19 Overview lactic acid bacteria metabolism (adapted from Swiegers et al. [14])

Table 2.1 LAB growth and MLF in different winemaking roles

Wine style	Wine making benefits of MLF
Cool-climate white wine	De-acidification
Sparkling base wines	De-acidification and sensory improvements
Full-bodied white wines	Sensory improvements
Red wines	Sensory improvements and increased microbiological stability

detrimental and winemakers will actively discourage it. However, it can also serve a variety of winemaking roles as outlined in Table 2.1.

In these cases MLF will be encouraged and similar considerations to those made with managing alcoholic fermentation can be applied. In cases where MLF needs to be discouraged the winemaker will need to manage wine conditions to discourage LAB growth. The key management tools are listed in Table 2.2.

The most important of these controls are bacteria type, bacteria numbers and temperature. This is especially true when other conditions such as pH or ethanol content are not in ideal ranges.

Some of the decisions around bacteria strain and numbers mirror those of yeast. Some winemakers will favour indigenous populations of lactic acid bacteria. At most wine pH and low SO_2 levels, *Oenococcus oeni* will predominate, however at

Table 2.2 Key management tools in discouraging MLF

Control factor	Management to encourage	Management to discourage
Bacterial numbers	Addition of large cell numbers by inoculation or starter cultures Minimise use of SO_2, lysozyme	Use of SO_2, lysozyme Clarification Pasteurisation Hygiene
Beneficial bacterial strain	Removal of indigenous bacteria via SO_2, lysozyme, pasteurisation clarification and hygiene controls Inoculation with selected strains *Oenococcus oeni*	Use of SO_2, lysozyme Clarification Pasteurisation Hygiene
pH control (target pH 3.3–3.5)	De-acidification	Acidification
Temperature	Maintenance of warm wine (18–22°C)	Refrigeration to below 15°C
Nutrition	Addition of nutrition. Maintenance of wine on yeast lees	Removal of wine from yeast lees. Minimise use of nutrition during fermentation
Growth factors and inhibitors	Use MLF positive yeast for primary fermentation. Addition of inactive yeast cells (ghosts/hulls)	Use of SO_2, lysozyme Use of MLF antagonistic yeast
Ethanol	Decrease alcohol content	Increase alcohol content

elevated pH or very low SO_2 levels, other bacteria like *Lactobacillus* var and *Pediococcus* var may also occur. Again, analogous with yeast, bacteria will all have varying abilities to carry out successful MLF including the production of positive or negative sensory characters.

To ensure a greater degree of success, many winemakers will inoculate wines with large numbers of selected *O.oeni* strains. These strains will be better adapted to the hostile conditions of the wine as well as producing less problematic chemicals such as acetic acid, ethyl acetate, acetoin and biogenic amines. They can also be added in large enough numbers so that a viable population is quickly established and the bacteria can therefore move onto MLF quicker.

It should be noted that LAB growth is considerably slower than yeast growth. Also, as the yeasts grow during alcoholic fermentation they will actively suppress LAB growth so that MLF usually occurs post alcoholic fermentation. This can be problematic as alcoholic fermentation can often extend into later parts of autumn/fall, leaving MLF to occur during the coldest months of the year. This does cause the winemaker problems as there is a need to maintain a constant wine temperature of 18–22°C throughout winter until MLF completes. Alternatively, some winemakers will wait until spring and the natural warming of wine cellars and wines to allow the MLF to complete. Maintenance of the winemaking conditions which are conducive to MLF will, however, also allow microbiological spoilage by other organisms such as *Brettanomyces*. Therefore, winemakers will generally avoid a lengthy MLF in order to reduce the risk of spoilage.

2.6.3 Microbiological Spoilage

Winemaking can be said to be a microbiological process and this is definitely the case with processes involving alcoholic fermentations. In addition, some wine styles also require the successful metabolism of malic to lactic acid to help realise winemaking requirements. Apart from these two key winemaking events, most winemakers will consider that any other microbial activity is detrimental to the desired wine style due to the fact that this activity will result in unwanted by-products such as acetic acid and ethyl acetate (vinegar and solvent aromas), 4 ethyl phenol (barnyard and Elastoplast® aromas) and ethanal/acetaldehyde (nutty, bruised apple aromas) or unwanted physical and chemical changes such as dissolved CO_2, hazes and deposits. Therefore winemakers will actively attempt to control microbiological populations through various strategies. The main strategies include:

- Use of microbial control agents
- Filtration and micro-organism removal
- Pasteurisation
- Other sterilising techniques
- Control of wine environment
- Cleanliness and winery hygiene

The most common method is the use of anti-microbial additives including sulphur dioxide, sorbic acid, dimethyl dicarbonate or lysozyme. These are used at levels which decrease micro-organism populations and stop them growing. Control will be maintained as long as the agents persist in the wine. Once agent levels drop to below minimum use levels, spoilage can re-occur.

Micro-organisms are large enough that they can be effectively removed through fine filtration. Simple depth filters rated at 0.45 or 1 micron can be used to significantly reduce yeast and bacteria numbers. Absolute rated membrane filters of 0.2 or 0.45 micron can be used to completely remove micro-organisms as long as the filter integrity is maintained. It should be noted that after filtration wine must be kept aseptic otherwise micro-organisms can be re-introduced and spoilage can occur. It is vital that filtration equipment is heat sterilised (by steam or 80°C hot water) prior to use in order to ensure the equipment itself is not a source of downstream contamination.

Wine and juice can be pasteurised to sterilise the liquid and kill unwanted organisms. Liquid temperatures need to be maintained at pasteurising temperatures of 55–60°C plus for the required holding time (1–4 min) prior to cooling. Rapid increases and decreases in temperature are required to minimise negative sensory change to the liquid. After cooling, the liquid will again be susceptible to re-infection and spoilage. An additional effect of pasteurisation is denaturing of proteins and enzymes which can minimise effects of oxidative enzymes such as Laccase from *Botrytis* grapes.

Other sterilising processes have been developed as alternatives to pasteurisation and include the use of UV light (Surepure®), ultra sound (Cavitus®) and pulsed electric fields [12]. These techniques promise energy saving or minimal disruption to the sensory character of wine. As with other physical techniques, there is no residual anti-microbial activity and liquids are still susceptible to spoilage post treatment.

Control can also be achieved through management of the wine environment to minimise growth of these spoilage organisms. This can be done through removal of substrates and nutrition, management of pH, control of temperature and exclusion of oxygen. Whilst techniques such as substrate removal or pH control may have an impact on wine style, the use of oxygen control and refrigeration can be very effective at controlling spoilage.

Finally, winery hygiene is important to minimise the populations of unwanted microbes within the winemaking environment. Early on during grape processing, the juice is at its most susceptible to microbiological attack, due to large indigenous micro-organism population and abundance of sugar and nutrition. For winemakers to effectively control spoilage they are often required to involve multiple control strategies, commonly employing regular and effective cleaning of tanks and equipment, widespread use of SO_2 and employing low storage temperatures of $<10°C$.

2.6.4 Juice or Pre-Ferment Clarification

After grape processing and pressing there are often excessive levels of solids within the grapes juice. These grape solids are made of fragments of skin, seeds and stems, macromolecules such as proteins, pectins, phenolics and tartrate precipitates. If the juice was to enter fermentation at this time there would be a tendency for very excessive yeast growth, high fermentation rates and the production of heavy sulphide aromas and flavours. Ferments conducted with high solids are difficult to control and tend to finish quickly. Whilst acceptable in some styles of wines, it is detrimental to most wine styles, so to avoid these effects there is a need for a clarification step post-ferment.

This clarification step can be achieved through a variety of different methods. Traditionally the juice is held static, until the juice clarifies naturally (taking between 12 and 36 h). This process can often be speeded up with the use of pectinase enzymes which break down pectins, decreasing viscosity and improving aggregation and settling. The juice must, however, remain static and therefore any microbial activity needs to be minimised. If yeast is active during this stage there will be a production of carbon dioxide. Any solids can then adhere to the rising bubbles and be lifted back into suspension (lifting lees) and consequently decrease juice clarity. These factors mean that most juice settling is undertaken in conditions of adequate SO_2 and low temperatures of $<10°C$. Alternatives to traditional juice settling do exist and include filtration systems, centrifugation systems and

flotation systems. In these, the clarity is achieved through methods other than gravitational sedimentation.

After clarification there is usually a significant volume of juice lees, that is, juice with a significant percentage of solids (5–10%). These lees will often be recovered through filtrations (DE Lees filters or Rotary drum vacuum filter) or centrifuge. This recovery is important because it can often constitute a significant proportion of process volume and can often give considerable positive flavour levels from the contact with the skins.

2.6.5 Maceration on Skins: White Wines

A grape berry consists of several distinct regions, each containing differing levels of key grape chemicals. Whilst the pulp and juice of the berry in rich is sugar and acid, it is comparatively poor aroma, flavour and polyphenol compounds. Wine made entirely from pulp juice will tend to be a delicate style. To obtain wine styles with more mouth feel, body, colour, aroma and flavour, there needs to be an exchange between the juice and the skin of the berry. This is achieved through the maceration process where the skins remain in contact with the juice or wine after crushing/de-stemming.

In the case of selected white wine styles, maceration is often employed to enhance mouth feel, body and flavour. However, excessive polyphenol or colour pick-up is best avoided as it will soon dominate wine characters. The best extraction of favourable compounds is achieved through a short period of low temperature maceration after crushing. This should be 5–10°C, and should last from 3–12 h in which the beneficial characters are noticeably increased whilst the negative characters are avoided. Longer or warmer macerations tend to result in astringent and highly coloured wines.

2.6.6 Maceration on Skins: Red Wines

In the case of red wine styles, this maceration process lasts for a long period of time and occurs concurrently with alcoholic fermentation and possibly malolactic fermentation. This extended period of time usually lasts 5–7 days but can be extended over a matter of weeks or even months.

During fermentation the grape skins present in the liquid will trap the carbon dioxide bubbles and will be taken to the surface of the wine where they form a semi-solid mass known as the cap. This cap of skins will slowly drain off liquid and the process of extraction of colour, polyphenols, flavour and aroma will slow and stop. Also occurring co-currently with the decrease in liquid content is the increase in heat retention in the cap. High yeast numbers are located in the cap which, coupled with the insulation effect of the skins and decrease in convective

Table 2.3 Common cap management techniques

Name of cap management	Description
Punchdown, plunging, pigeage	The floating mass of skins are periodically pushed down into the ferments by physical means
Pump over, jetting, remontage	Fermenting wine is drawn off the bottom of the tank and passed back over the top skins
Rack and return, delestage	Fermenting wine is drawn off the bottom of the tank to a separate vessel. It is then rapidly pumped back onto the skins flooding the cap
Submerged cap	The mass of skins is held submerged due to the presence of screens located below the liquid level
Inert gas mixed tanks, Ganimede®	A large volume of inert gas is introduced into bottom of the tank. As the bubbles travel through the wine they cause the cap of skins to collapse and sink

heat transfer, will result in elevated temperatures which will affect the products of fermentation as well as yeast viability. To stop the heating up and drying out of the cap, a variety of different techniques are employed to keep the mass of skins in contact with the fermenting wine. The most common techniques are outlined in Table 2.3.

Whilst cap managements can help regulate cap and wine temperatures they are often not capable of limiting fermentation temperatures to desired ranges. Cap managements are, therefore, done in conjunction with refrigeration activity to ensure the wine conditions are homogenised and temperatures are maintained at the desired levels.

2.6.7 Stabilisation

After fermentation and maturation, wine will undergo a variety of chemical and/or biological reactions. If these chemical reactions have not been completed by the time of packaging they occur once retailers and consumers have acquired the wine, which may lead to wine being rejected.

In wines that are matured in wineries for significant periods of time, the key instability reactions will occur while the wine is in storage, and the wines will become naturally more stable. This is especially true when barrels are used in conjunction with extended contact between the wine and yeast lees. Young wine styles need to be released to market early and so can be at added risk of instability due to their relative youth.

Many of the chemical instabilities can be managed through careful use of additives and processing aids. Examples include the use of bentonite montmorillate clay which can be effective at reacting with and consequently removing heat labile proteins. Use of ascorbic acid or PVPP fining agents can significantly reduce

the occurrence of Pinking (when unstable phenolic material in the wine turns grey/pink). Iron case contamination can be combated through the use of citric acid.

Of particular interest is the case of cold or potassium bitartrate instability which occurs post fermentation. Wine grapes are rich in tartaric acid, bitartrate and tartrate ions. It is particularly problematic when bitartrate ions react with potassium to form insoluble potassium bitartrate (KHT); potassium bitartrate has poor solubility in ethanol, so as fermentation progresses the wine becomes supersaturated with KHT. This excess KHT will crystallise once conditions become favourable. Winemakers have two main controls for this problem; suppress crystal growth via additives and inducement of crystal growth.

The use of additives such a metatartaric acid, gum Arabic, mannoproteins and carboxymethylcellulose (CMC) can either temporarily or permanent suppress KHT crystallisation. This stops the instability from forming, leaving the finished wine in a good sales condition.

Inducement of crystal growth is usually achieved through the use of refrigeration. This is because solubility of KHT is very dependent on temperature, so low wine temperatures result in a larger degree of bitartrate super saturation. This in turn results in a greater physical drive for crystallisation and the wine will become stabilised. This process will occur naturally over time at low temperatures, for example in winter, or can occur more quickly when refrigerated to low temperatures (-3–0°C). The process can be further enhanced through the addition of seed crystals of cream of tartar. If used at the correct temperature and with adequate quantities (1–4 g/l), these seed crystals can rapidly stabilise wines. This process tends to be expensive, energy intensive and time consuming and alternatives to cold stabilising are available. These include the use of ion exchanges columns or electro-dialysis.

2.6.8 Wine or Post-Ferment Clarification

Wine can often contain significant levels of solid material, primarily yeast and yeast debris. Whilst the bulk of the solids in wine are yeast derived there can also be significant levels of bacteria and bacterial debris. Other solids such as condensed polyphenols, potassium bitartrate and calcium tartrate crystals and macromolecules from protein to polysaccharides also exist. Many of these solids contain positive or negative charges and can form colloidal dispersions which resist natural flocculation and sedimentation. Generally, most wine consumers demand a high degree of clarity in their wines. Therefore, a winemaker must take active steps to clarify their wine prior to bottling. This improves saleability and can aid in the prevention of spoilage.

The most traditional method of achieving clarity can be done through periods settling followed by racking. After each racking, the wines clarity will improve, especially if it occurs within small oak barrels. However this process can be time consuming, cumbersome and yield poor results especially if the wine undergoes

any temperature fluctuation where natural convection currents stir the wine up. Also this natural clarification does not allow for the absolute removal of micro-organisms and so potential spoilage may still occur.

Often, the long and drawn out racking process can be replaced with faster clarification processes, most notably centrifugation and filtration. With centrifugation, turbid wine can be slowly passed through a high speed hermetic separator centrifuge. Here the wine is subject high radial speeds, which causes an accelerated sedimentation due to the high levels of centrifugal force. Depending upon on the desired throughput as well as the nature of the wine turbidity, high degrees of clarity can be achieved. Most wineries rely on some form of filtration to achieve the desired level of clarification.

As can be seen in Table 2.4, there are a series of filtration options available and winemakers will choose a variety of complimentary techniques to suit their winemaking aims. Filtrations down to molecular levels (Nano, Ultra and RO) can be achieved with tangential filters and allows the wine chemistry to be altered. However, these systems often operate at very high pressures to achieve high through-put.

2.6.9 Oxygen and Oxidation

Wines and juices have a complex chemical and biological relationship with oxygen, which is still being researched. On the whole, juices and wines need to be protected from oxygen contact otherwise oxidation will occur. However, on occasion wine and juice will benefit from controlled oxygen contact.

2.6.9.1 Oxidation

The exposure of wine and juice to oxygen can result in the degradation of wine polyphenols, aroma and flavour. It can also cause the accumulation of sensory defects such as ethanal, acetic acid and ethyl acetate. Whilst oxygen cannot react directly with wine and juice, it can react via intermediary chemicals, catalysts and enzymes [5]. It can also react via microbiological metabolism, most notably acetic acid bacteria (AAB) and mycodermic yeast. The most damaging form of oxidation is the microbiological processes which result in the production of ethanal and volatile acidity by AAB and mycodermic yeast. These aerobic micro-organisms grow on the surface of the wine when oxygen is present and metabolise ethanol in a reversal of the normal fermentation process, as shown below.

$$\text{Ethanol} \rightarrow \text{Ethanal} \rightarrow \text{Acetic acid} \rightarrow \text{Ethyl acetate.}$$

This results in a significant bruised apple, vinegar and solvent defects in the wine. Control can be achieved in a variety of ways. The most effective is to limit

Table 2.4 The various filtration options available

Direction of flow over media	Style	Filter media	Type	Filtration role
Perpendicular	Depth	Diatomaceous earth or Perlite	Rotary drum vacuum filter RDV or RDVF or RVF	Recover of lees Clarification of very turbid wines
Perpendicular	Depth	Diatomaceous earth or Perlite	Plate and frame Lees filter	Recover of lees Clarification of very turbid wines
Perpendicular	Depth	Diatomaceous earth or Perlite	Pressure leaf filter or Earth filter	Medium turbidity wines Low turbidity wines
Perpendicular	Depth	Cellulose	Plate and frame filter Pad or Sheet filter	Medium turbidity wines Low turbidity wines Microbiological reduction
Perpendicular	Depth	Cellulose	Lenticular cartridge filter	Low turbidity wines Microbiological reduction
Perpendicular	Surface	Polymer	Membrane	Microbiological sterility
Tangential	Surface	Polymer Ceramic	Cross-flow filter	Medium turbidity wines Low turbidity wines Microbiological reduction
Tangential	Surface	Polymer Ceramic	Ultra filtration Nano filtration	Removal of alcohol Removal of water (*enrichment*) Removal of taints Removal of Macro-molecules
Tangential	Surface	Polymer Ceramic	Reverse osmosis	Removal of water

contact between wine and oxygen, which can be achieved by keeping wine tanks full or use inert gases such as nitrogen, carbon dioxide and argon to exclude oxygen from the wine. The second method is limit microbiological growth by using low temperatures, sterile filtration and anti-microbiological agents such as sulphur dioxide.

Another type of oxidation is the enzyme catalysed oxidation of wine juices. In this situation, oxidase enzymes, such a tyrosinase (polyphenol oxidase) found in healthy grapes or laccase found in botrytis grapes, significantly accelerate oxidation juices. The action of the oxidase enzymes can be minimised by the following strategies:

Table 2.5 Beneficial oxygen contact

Role	Benefit
Hyper-oxidation of juice (saturation of juice with excessive oxygen)	Removal of unwanted colour and poly-phenols
	Improved stability
Improvement of fermentation	Increase yeast bio-mass production
	Increase utilisation of nutrition
	Improved resistance to ethanol toxicity
	Removal of reduction aromas (H_2S etc.)
Splash racking	Removal of reduction aromas (H_2S etc.)
Micro-oxygenation	Removal of reduction aromas (H_2S etc.)
	Reduction of vegetal/herbaceous aromas
	Improvement of sensory attributes most notably by increased polyphenol reactions
	Improved colour stability

- Removal of Tyrosinase by use of sulphur dioxide and bentonite
- Reversal of oxidation damage and quinone formation by use of sulphur dioxide
- Reduction in the oxidation rate by lowering the juice temperature
- Removal of oxygen by use of an inert gas to exclude oxygen from processing

The last type of oxidation is that of iron and copper catalysed auto-oxidation and the strategies for managing this type of oxidation include:

- Reduction in oxidation rate by lowering the juice or wine temperature
- Removal of oxygen by use of an inert gas to exclude oxygen from processing
- Removal of catalysing metal ions

The use of sulphur dioxide is important in oxidation control as it plays a role in reversing quinone formation and reacting with peroxide ions. It can also reduce microbiological action and denature tyrosinase enzymes. Ascorbic acid (Vitamin C) can have an anti-oxidant effect in wine but it must be used in conjunction with sulphur dioxide otherwise it can take on a pro-oxidant role in wine.

Almost all negative effects of oxygen can be managed by a winemaker using correct levels of sulphur dioxide, using inert gas to minimise contact between wine and juice with oxygen and reducing liquid temperatures to slow overall reaction rates.

2.6.9.2 Oxygen Contact

While oxygen contact is usually detrimental in winemaking, in certain cases it can be beneficial. The beneficial effect of oxygen is outlined in Table 2.5. In these situations, winemakers will actively allow small and controlled amounts of oxygen to react with the wine, to achieve a desired effect.

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Chapter 3
Solar Technology

3.1 Brief History

Human civilisation has long recognised the crucial role that the sun has played in sustaining life on our planet and as such it has been given a central role in religious practice and mythological chronicles through the ages; Ra in ancient Egypt, Tonatiuh in the Aztec culture, the ancient Greek God Helios or Sol in the Roman Empire to name a few. However, whilst many structures were made associated with worship of the sun, such as Stonehenge or the Step Pyramids in Central America, they were not associated with the capture of solar energy for human comfort or benefit.

Socrates first mentions the issues associated with the heating and cooling of dwellings in ancient Greece. The unrestricted use of indigenous forests to supply wood for heating led to a severe reduction in fuel availability and gave rise to the drive for alternative sources. Fortunately, solar energy was a readily available substitute and led Greek architecture to develop both means of 'cooling' during the summer months through thermal mass and access to the sun's rays during the winter season for solar heating and daylight [2]. Indeed, not only were individual dwellings designed on solar principles, entire cities were planned to maximise solar capture, minimise shading and reduce dependence on wood fuels.

Likewise, the Romans had significant issues with heating their buildings. If anything this problem was greater due to the wider variation in climatic conditions encountered across the empire and increased deforestation because of the heavy reliance in wood as a fuel, from the widespread use of the hypocaust as a heating system through to the level of industrialisation in activities such as metal working. The Romans too adopted the art of solar architecture, but they advanced the architecture of the Greeks by adding glass into building openings, thus giving rise to windows, greenhouses and atriums.

The introduction of glass represented a significant step forward in the performance of solar capture technology. This simple structure allowed short-wave solar radiation to pass into the building space, whilst keeping the unwanted vagaries of

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the external environment out, such as rain, wind and snow. Once in the building the surrounding building structure increases in temperature through solar absorption, but due to the long-wave nature of radiation being emitted from these surfaces, the energy is trapped…. the classic 'greenhouse effect'. The benefit of this 'solar trap' was not lost on the Romans, and many variations of the basic principle were incorporated into Roman buildings. The glazed caldarium is a good example of enhanced space and water heating design and a detailed understanding of solar interactions was demonstrated through adding darkening agents to floor surfaces to improve solar absorption and thus heat gain. The use of the 'metal reflector' too would have significant impacts for solar capture, but early accounts of reflectors with solar energy recall their use as weapons of mass destruction. It was not until the time of Leonardo da Vinci, that solar reflectors would find a peaceful role and be used in the capture of solar energy for heating purposes.

Following this early understanding of the principles involved in solar transfer and improvements in glazing, reflective and absorption materials, the applications for solar energy utilisation was set to expand significantly. However, the advent of the middle ages, certainly for Europe, meant that solar technology development took a step back and it was not until the sixteenth century that a renewed interest in solar energy started again, primarily in horticulture. Just as the Romans had used 'greenhouse' technology to increase the growing season for fruits and vegetables, Europeans quickly started to develop their own greenhouse designs, in particular, Northern Europe due to the 'poor' climate was quick to adapt new systems that could improve production yields.

The ability of glass to trap heat from the sun received widespread interest in the eighteenth century due to the advent of cheaper and larger panes of glass, resulting in more use of greenhouses and conservatories. De Saussure carried out the first recorded scientific investigation of this heat-trapping ability of glass. He constructed a miniature multi-walled greenhouse from five glass boxes set on top of one another and measured the temperature inside each layer. He found that the inner box reached a temperature of 87°C but could not explain the physics of his system. De Saussure also constructed a 'Solar hot box', illustrated in Fig. 3.1, which achieved temperatures as high as 110°C. This solar hot box was in fact a basic ICS (Integrated Collector Storage) air heater [2].

The first true solar water heater was in fact an ICS system. They simply consisted of exposed tanks of water left out to warm in the sun. Used on a few farms and ranches in the southwest of the USA in the late 1800s, they were reportedly capable of producing water hot enough for showering by the late afternoon on clear days [2]. The first solar water heater, manufactured commercially under the trade name 'The Climax Solar-Water Heater' was an Integrated Collector Storage Solar Water Heater (ICSSWH) patented in 1891 [4]. A reproduction of the original patent is shown in Fig. 3.2.

This water heater could be used from April to October in the state of Maryland in the eastern USA, producing water hotter than 38°C on sunny days even, it was claimed, during early spring and in late autumn when daytime temperatures sometimes approached freezing. The unit, shown in a reproduction of an original

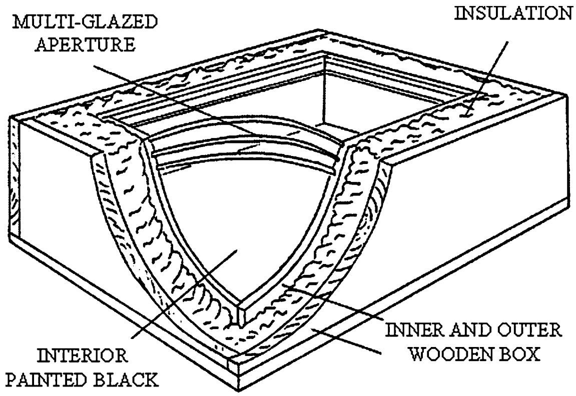


Fig. 3.1 A ‘solar hot box’ of the type probably used by De Saussure in the nineteenth century (adapted from [2])

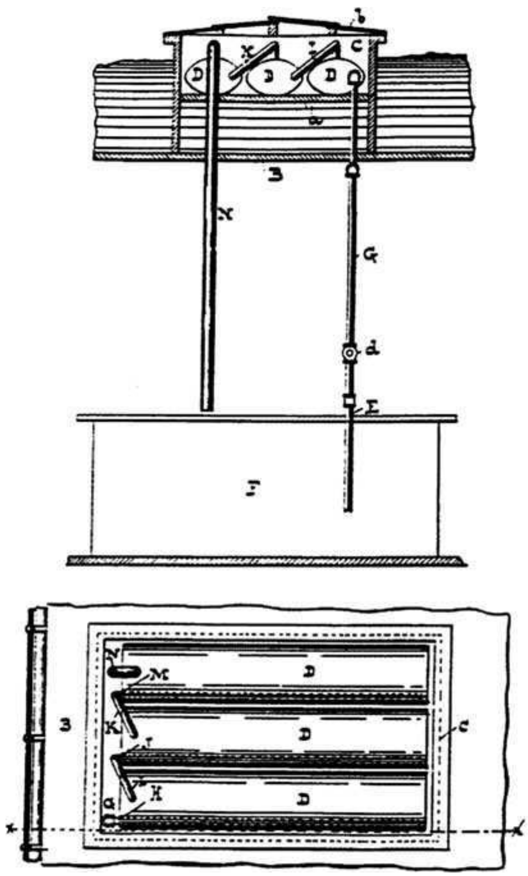


Fig. 3.2 Reproduction of Kemp’s patent for an apparatus for utilising the sun’s rays for heating water [4]

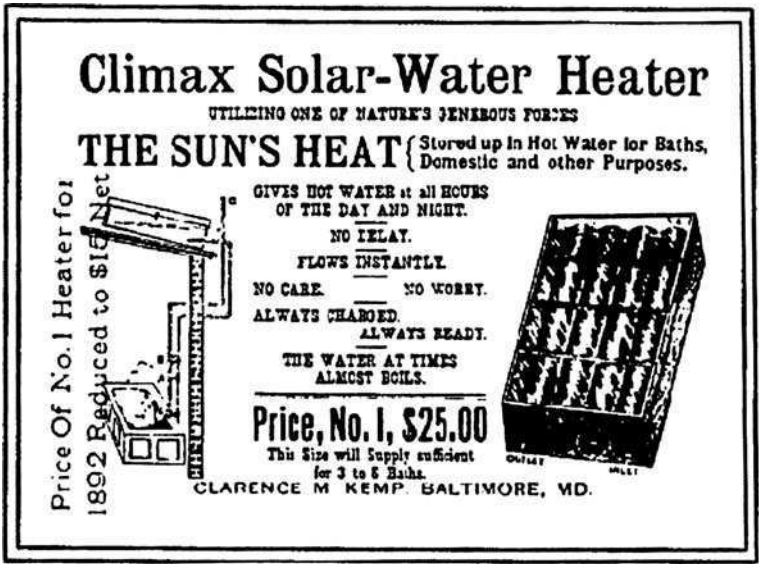


Fig. 3.3 Advertisement for the climax solar water heater, 1892 [2]

advertisement in Fig. 3.3, was simply four small (29 l) heavy galvanised iron cylindrical vessels, painted a dull black and mounted in a wooden box insulated with felt paper, under a single-glazed aperture. From these early 'modern' solar water heaters, a large array of different systems has evolved to provide heat for a wide range of applications.

Solar (electric) power, however, is in historic terms, quite a new development. The first recorded production of useful power from the sun goes to the solar powered steam engine invented by Auguste Mouchot and his assistant Abel Pifre in 1861. At the time he stated that fossil fuels had a limited future. A short sighted statement during the Industrial Revolution of the nineteenth century, but in today's current situation a very prophetic warning, and perhaps a statement ahead of its time (Fig. 3.4).

However, the development of true solar electric power, that is a process that directly converts solar radiation into electricity and does not require an intermediate thermal conversion process, goes to the photovoltaic (PV) device. Although the PV effect was first described by the French physicist Edmond Becquerel in 1839, who discovered that certain materials would produce small amounts of electric current when exposed to light, it remained a curiosity of science for several decades.

The PV effect was first studied in solids by Heinrich Hertz in the 1870s. Thereafter, PV cells made from selenium with conversion efficiencies of no greater than 2%, were produced, converting light to electricity. During the 1940s and early 1950s, when the Czochralski process was developed to produce crystalline silicon, more efficient PV cells were developed. In 1953, Bell Laboratories scientists

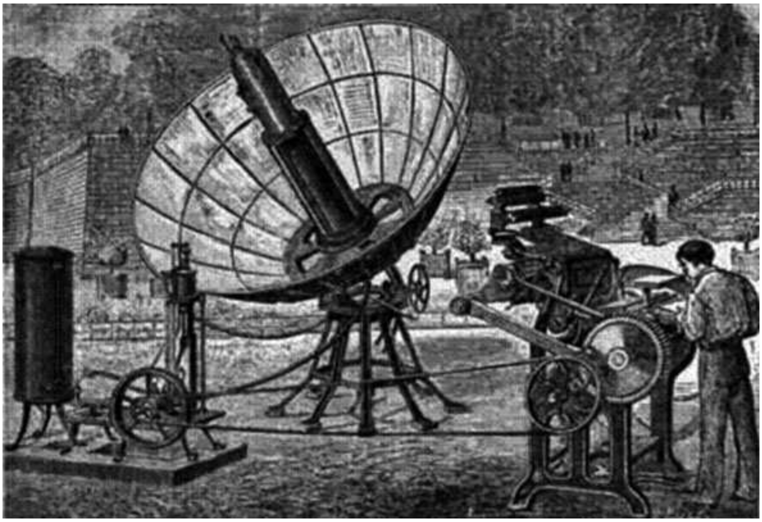


Fig. 3.4 Mouchot and Pifre's solar engine powering a printing press [5]

Gerald Pearson, Daryl Chapin and Calvin Fuller developed the first silicon solar cell capable of generating a measurable electric current and in 1956, although still far from an economic viability, the potential of solar PVs was already being proposed.

3.2 Solar Resource

The most important source of energy on the earth is the sun. Energy released by the sun is radiated outwards into space. Solar radiation is the general term used for this electromagnetic radiation emitted by the sun. Only a small fraction of this energy is received by the earth, but even so, its impact is vital for all life on earth. At the outer edge of the earth's atmosphere, the irradiated power of the sun falling on one square metre is called the solar constant and is usually given as 1.367 kW/m^2 (some fluctuation occurs but this is not significant for solar technologies).

Even though every location on the earth receives solar radiation, the actual amount can vary according to the geographic location, time of day, season and local landscape and weather. Due to the earth's round shape solar radiation is incident on the surface at different angles, ranging from 0 to 90°. When the sun is directly overhead, at 90°, the earth receives the maximum energy possible. At this point, the Air Mass Factor is one, as it gives the minimum distance that the sun's rays have to pass through the earth's atmosphere. As the angle of the sun's elevation falls, the sun's rays travel a longer distance through the earth's atmosphere,

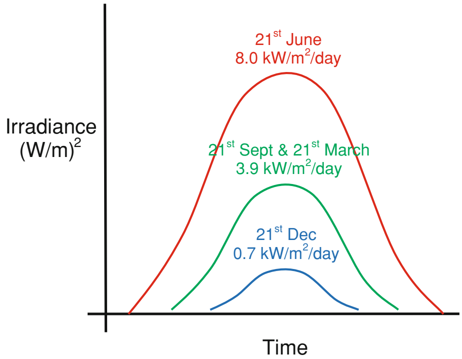


Fig. 3.5 Daily irradiance distribution for London, UK

reducing in intensity as the energy is scattered and diffused. It is for this reason that the further one travels from the equator, the lower the solar resource.

Whilst some variation in the earth's rotation around the sun occurs, the earth's axis of rotation is a greater factor in determining the amount of solar radiation striking at a particular location. The earth rotates on an inclined axis (±23.5°), receiving the sun's energy in a rhythmic pattern throughout the year. Because of the tilt in the earth's axis of rotation the sun's radiation shifts from north to south during the year (commonly referred to as the declination of the sun). This declination gives rise to the seasons with their different intensities (and thus energy received) and varying the lengths of day and night. In addition, the very rotation of the earth is also responsible for hourly variations in sunlight, with maximum energy being incident at solar noon (Fig. 3.5).

When solar radiation passes through the atmosphere, some of its energy is absorbed, scattered, and/or reflected. This is primarily through moisture is the air, but also by airborne pollutants. This radiation is termed diffuse radiation. Solar radiation that is not redirected in its path to the earth is termed direct (beam) radiation. The sum of diffuse and direct radiation is known as global solar irradiance. Atmospheric conditions can reduce direct (beam) radiation by 10% on clear, dry days and up to 100% during thick, cloudy days. The average annual global solar irradiance is a key factor in designing any solar collection system. In many instances, solar maps are produced, based on the average global solar irradiance (measured in kWh/m^2 per day on a horizontal surface), and can be a useful tool in system selection. Of course, in solar technology, systems are not always mounted in a horizontal position. They are more commonly tilted to improve solar collection for a given location. Figure 3.6 illustrates the key solar angles for a northern hemispherical location.

Where α_s = solar azimuth; γ_s = angle of sun's elevation; α_c = collector azimuth; β = inclination of collector.

The influence of the collector tilt on insolation (incident solar radiation) can be calculated for any location. In some cases, the calculated average annual totals of global solar irradiance for differently orientated surfaces can be represented graphically in contour plots, where lines of equal radiation (measured in kWh/m^2/year)

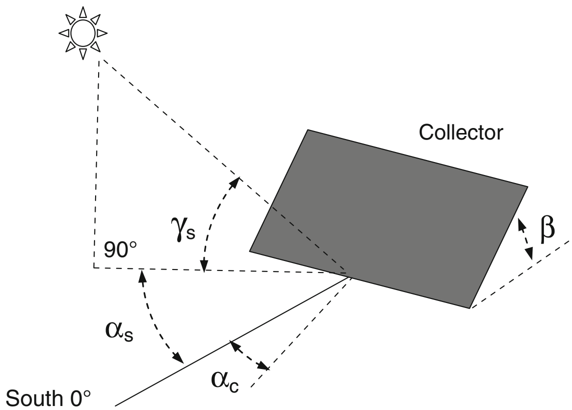


Fig. 3.6 Solar angles (for a northern hemispherical location)

can be determined against *X* and *Y* axis of azimuth and inclination angles, respectively.

The collection and conversion of solar radiation into usable energy can be accomplished by using many different forms of technology, including various direct and indirect methods. Generally speaking, there are basically two different methodologies used to collect solar energy; Passive solar and Active solar. Passive solar relates to the 'natural' capture of sun's rays using elements/structures/systems that do not use active mechanical systems. Active solar systems convert solar energy into usable light, heat, fluid movement or power using electrical or mechanical energy equipment to increase the usable collected energy. Figure 3.7 describes the classification of solar collection.

3.3 Passive Design

Passive solar refers to the collection, storage and redistribution of solar (thermal) energy without the use of any mechanical input. Passive solar applications, when included in initial building design, adds little or nothing to the cost of a building, yet has the effect of realising a reduction in operational costs and reduced equipment demand. It functions by relying on the integrated approach to building design (building elements and materials) and requires at least two elements.

- The collector (equator facing glazing).
- Energy storage element (thermal mass).

Good building orientation and internal planning are essential to attain optimised passive solar energy gain, although significant care must be given to avoid overheating and thus a detailed knowledge of site specific sun path interactions with the building and local environs is necessary. For small buildings in cold and temperate climates where the energy consumption is primarily dictated by the

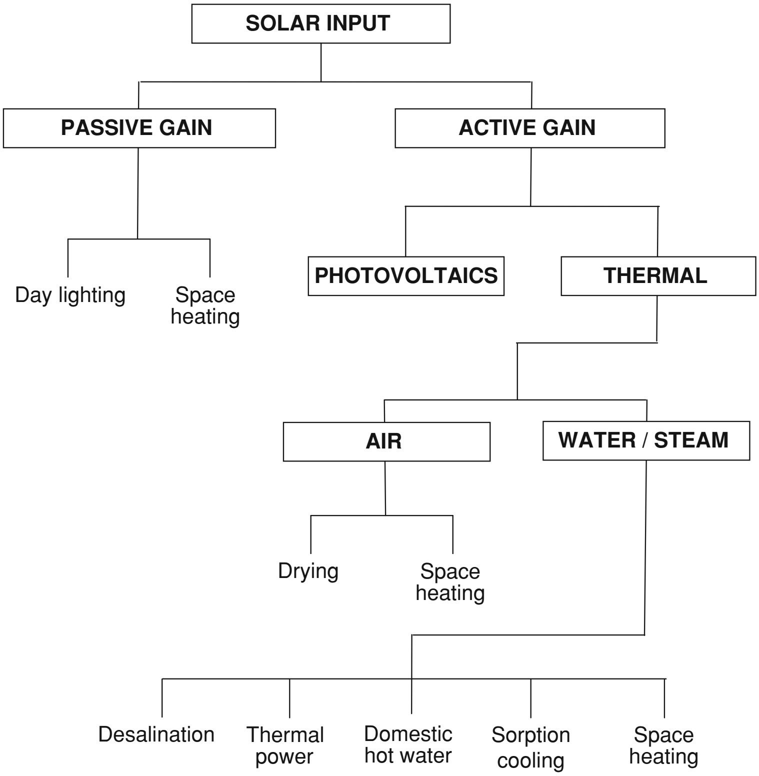


Fig. 3.7 Classification of solar energy collection

influence of the exterior climate on a building's envelope, passive solar design involves using solar energy to augment the space heating requirement. For other kinds of structures such as buildings in warm climates, where internal loads predominate, responsible passive solar design is more likely to concentrate on avoiding space cooling using good shading design and devices, high performance glazing and optimised day-lighting geometries.

Depending on climate, the passive solar design of an externally influenced building might include:

- Orienting more solar transparent elements towards the equator.
- Adoption of shading to avoid summer solar gain.
- Utilising significant thermal mass.
- Having appropriate insulation.
- Good HVAC equipment sizing.

And the passive solar design of an internal load dominated building might include:

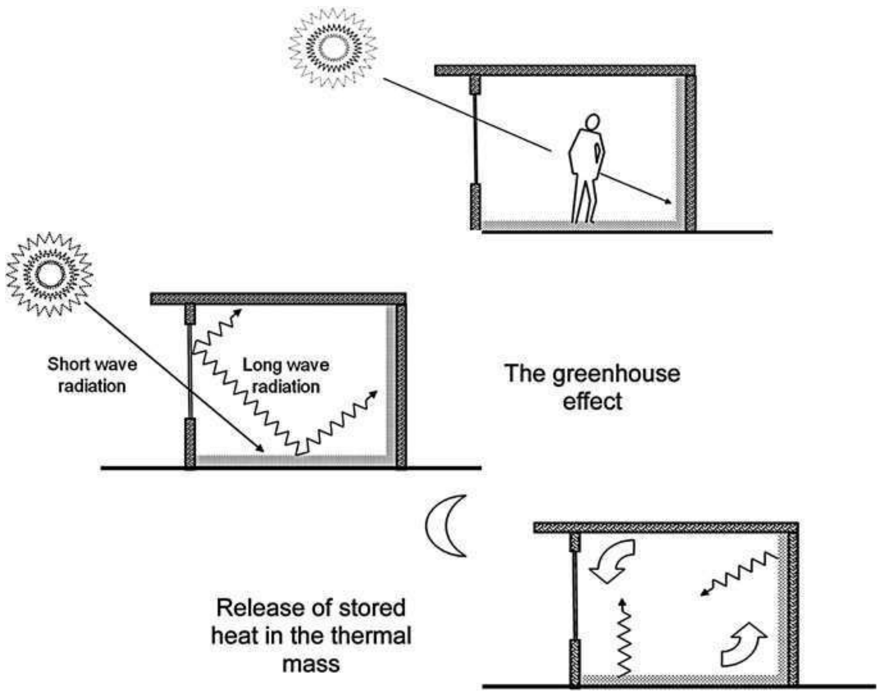


Fig. 3.8 Principles of direct gain

- Good day lighting through good orientation and control.
- Using high performance glazing (permitting visible light but reducing heat gain).
- Using high efficiency HVAC systems.
- Good shading provision.

There are three main configurations of passive solar design; direct gain, indirect gain and combined.

3.3.1 Direct Gain

Sunlight is admitted to the space (by an equator facing transparent/translucent element) and virtually all of it is converted to thermal energy. Figure 3.8 illustrates the basic working concept. The walls and floor are used for solar collection and thermal storage by intercepting radiation directly, and/or by absorbing reflected or re-radiated energy (Fig. 3.9).

The degree of solar gain must always be determined before the design is completed so that an appropriate passive solar design strategy can be adopted. The surrounding topography and/or buildings in tandem with the position of the sun,

Fig. 3.9 Direct gain in a corridor, with canvas (decorative) indoor shading devices

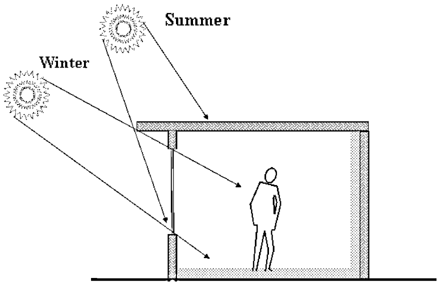


Fig. 3.10 Impact of the sun's elevation angle

as represented by altitude and azimuth angles, for a specific geographic location, season, and time of day must be known. Solar path diagrams, for example, allow the designers to determine the sun's position at any given time. This is vital in designing the building, landscape and/or devices to control the level of solar gain. Figure 3.10 illustrates how the simple use of an external overhang can prevent unwanted solar gain during the summer.

Direct gain design can employ a wide variety of materials and combination of ideas that will depend greatly upon the site and topography; building location and orientation; building shape (depth, length, and volume); and space use. Room finishes, furnishings and fixtures will have an impact on the collection and storage of solar radiation. The penetration of direct solar radiation is usually limited and thus other parts of the building are heated by convection. Heating of the rooms on the non-equator facing side of the building are better served by direct solar radiation. This can be effectively done via the use of a clerestory. Skylights, although not as good as clerestories, can still be off benefit especially if a reflector is used. Of course, these are only a couple of the many techniques used in direct passive design (Fig. 3.11).

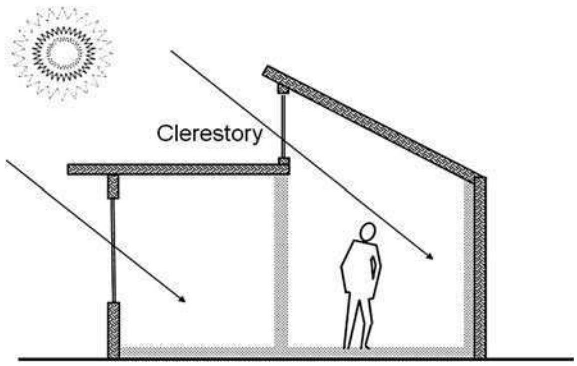


Fig. 3.11 Clerestory design to improve direct gain penetration

3.3.2 Indirect Gain

This passive solar design approach uses the basic elements of collection and storage of heat in combination with radiation and/or convection. In this approach, thermal storage materials are placed between the interior habitable space and the sun so there is no direct heating (Fig. 3.12). Instead a darkened thermal storage wall is placed just behind equator facing glazing (windows). This is sometimes referred to as a Trombe wall.

The passive Trombe wall collects heat without light entering the space. Then, due to the thermal time lag, most of the heat is released during the night. A variation to the Trombe can include high/low vents or half height walls to allow direct gain and day lighting (Fig. 3.13).

Water walls (solar closets), due to the greater specific heat capacity of water, can be a significant improvement on traditional concrete and brick materials. Any watertight container can be used but exposed (blackened) vertical steel tubes offer improved performance. Tubes made of translucent or transparent materials have also been used, producing thermal gain whilst allowing some light to pass through into the space. Care must be taken with regard to the growth of algae and the like within this basic system design.

3.3.3 Combined Direct and Indirect Solar

Another design approach takes advantage of the greenhouse effect as well as the direct gain storage wall. An equator facing sun space is constructed in front of a thermal storage element (wall) exposed to the direct rays of the sun (Fig. 3.14). This wall would be at the rear of the sunspace and the front of the primary structure. The thermal wall absorbs heat at the same time the interior space of the sunspace is being heated. During the day, the sun space collects solar radiation and distributes a portion to the rest of the building in addition to the thermal storage.

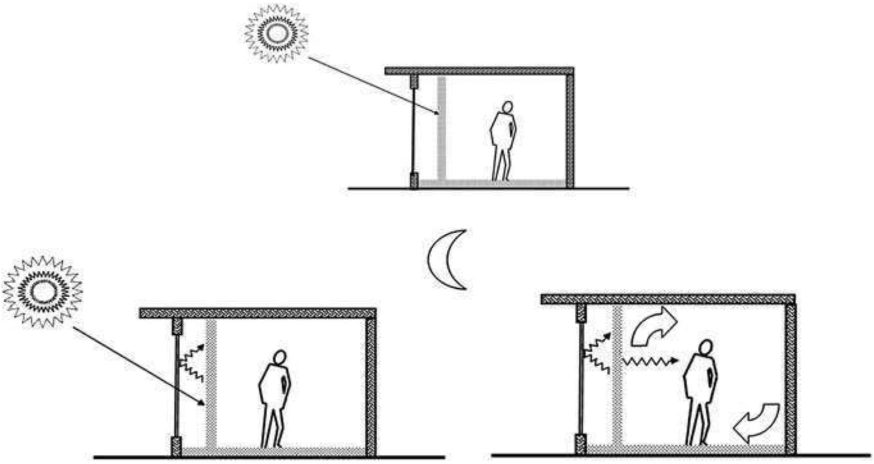


Fig. 3.12 The principles of indirect gain

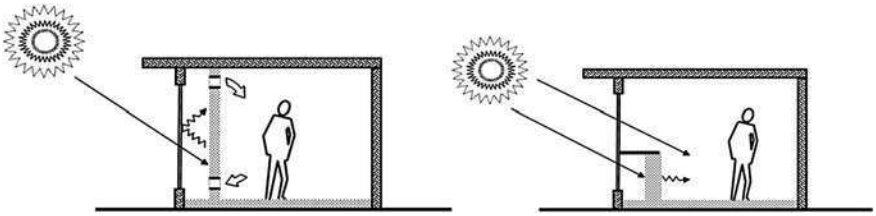


Fig. 3.13 Variations in the Trombe wall (vents and half height)

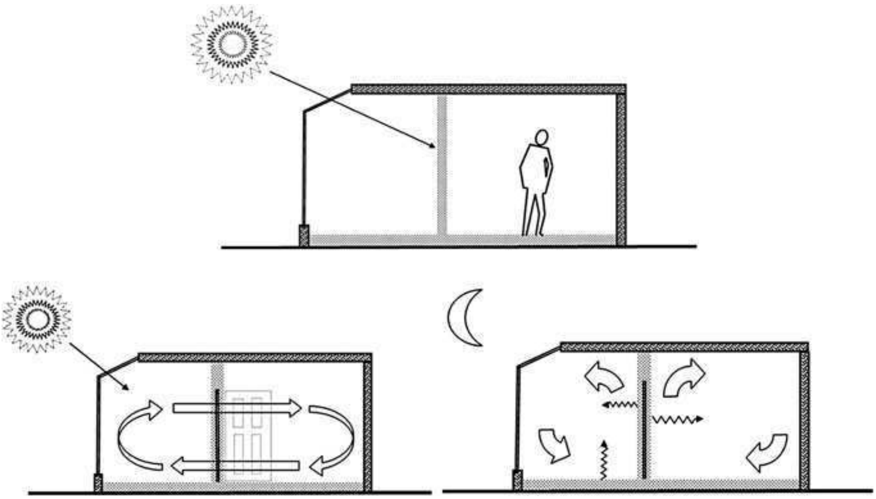


Fig. 3.14 The principles of combined solar gain

Fig. 3.15 Combined sun space feature

At night the sun space must be sealed from the main occupied space (Fig. 3.15). Figure 3.16 presents some design variations.

3.4 Photovoltaics

A PV cell is an electronic device that directly produces electricity from solar radiation. The term PV literally means light electricity; ‘photo’ from the Greek ‘phos’ which means ‘light’ and ‘volt’ after Alessandro Volta (1745–1827), an early pioneer in the study of electricity.

3.4.1 The Photovoltaic Effect

A crystal of silicon has a cubic structure where each atom has four electrons as shown in (Fig. 3.17). When looking at an entire network of silicon, each atom is held within the cubic lattice by sharing two electrons equidistant from itself.

By forming electron pair bonds with four neighbouring atoms, silicon achieves a stable configuration with eight outer electrons. The bond however can be broken by the action of light and the electron is then free to move and leave a hole in the lattice, giving rise to intrinsic conductivity. Intrinsic conductivity will not produce electricity and therefore in the case of silicon, impurities are deliberately introduced into the lattice. These are known as doping atoms and are necessary to create two thin layers of dissimilar semi-conducting materials—‘p’ and ‘n’ type

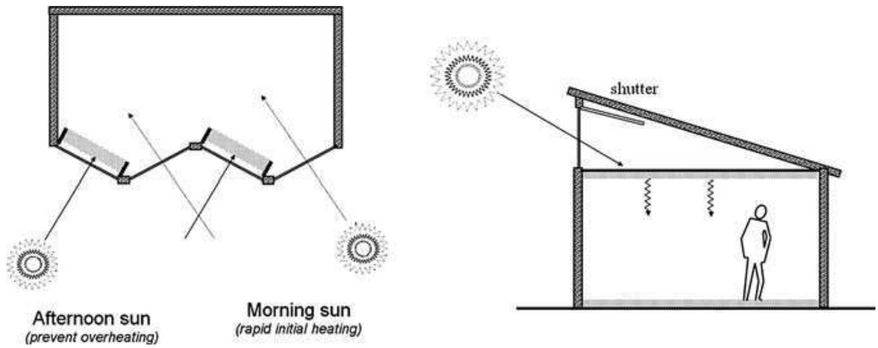
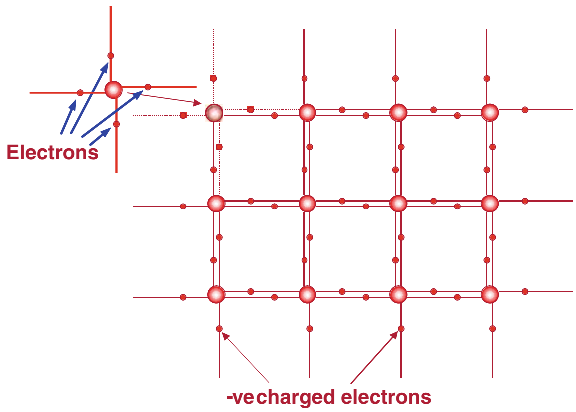


Fig. 3.16 Variations in combined gain collection

Fig. 3.17 The cubic lattice structure of pure silicon



semiconductors. A crystal of n-type silicon can be created by doping the silicon with trace amounts phosphorous, which has five electrons, giving an extra electron whist the crystal of p-type silicon is doped with trace amounts of boron, which has only three electrons, giving one less electron.

In the n-doped (phosphorous) lattice, the surplus electrons are now free to move in the crystal. In the p-doped (boron) lattice there is a hole in each boron atom and thus electrons from neighbouring silicon atoms can move leaving a new hole elsewhere. This movement of electrons is called extrinsic conduction but in each doped material the free charge has no direction. The amount of energy possessed by any given electron in a material will lie within one of several energy levels or bands. The electrons that normally hold the atoms of the material together are in what is known as the valence band. When electrons acquire higher energy levels, sufficient to 'jump' to the next layer or energy band, this is known as the conduction band. The difference between these two layers is known as the energy gap and varies from material to material.

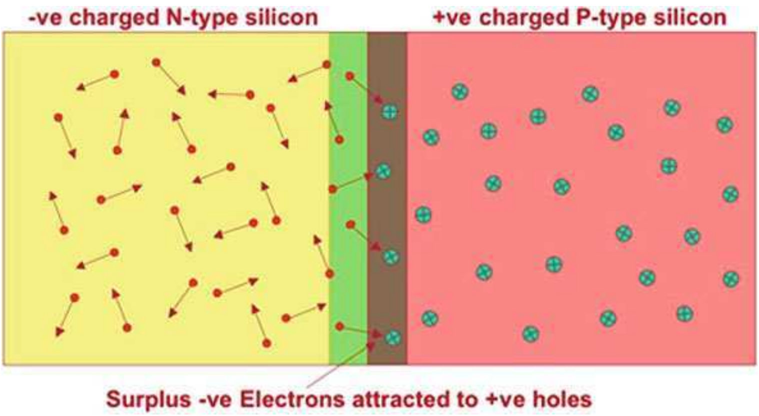


Fig. 3.18 Formation of the space charge region

When ‘p’ and ‘n’ type semiconductor layers are brought together, a junction is formed and thus a rudimentary PV cell is created. At this junction surplus electrons from the ‘n’ semiconductor diffuse into the ‘p’ type semiconductor layer, creating a region with few free charge carriers, known as the space charge region (Fig. 3.18).

If photons of sufficient energy strike an electron they will be promoted to the conduction layer, leaving a positive charged hole, creating what is referred to as an electron–hole pair. Holes left in the n-side of the depletion region (after being promoted) will be filled by the excess electrons from the p-side of the depletion region. Holes created on the p-side of the depletion region are filled by adjacent electrons in the p-type silicon. These holes will continue to be filled by adjacent electrons. The net effect is that they eventually “make their way” to the edge of the p-type silicon. Meanwhile electrons in the conductance layer will drift towards the edge of the n-type silicon. The flow of electrons to the n-region is, by definition, an electric current. If an external circuit for the electrons (current) to flow is created, the electrons will flow out of the semiconductor via metal contacts on the n-side of the cell. Similarly the holes close to the other metal contact on the p-side of the semiconductor will be filled by electrons entering the other half of the circuit (Fig. 3.19).

In order to be able to take power from the PV cell, metallic contacts must be applied to the front and back of the cell (Figs. 3.20, 3.21). Silver is the most widely used metal for contact formation. Silver in the form of a paste is screen printed onto the front and rear. In the front, to allow as much light through as possible, the contact usually takes the form of a grid like structure. In addition, aluminium paste is applied to the rear to achieve Back Surface Field (BSF) which improves the performance of the cell. These metal pastes are subsequently heated above the alloying temperature to create a good ohmic contact. To further reduce surface reflection, the cells are coated with an anti-reflection coating (ARC) such as silicon nitride or titanium oxide.

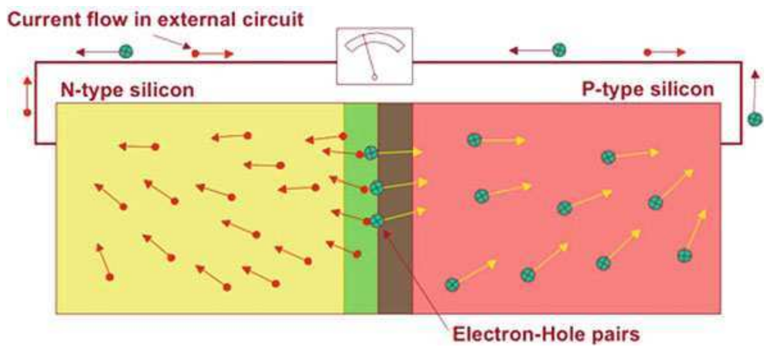


Fig. 3.19 Flow of electrons with an external circuit

Fig. 3.20 Section through the basic PV cell

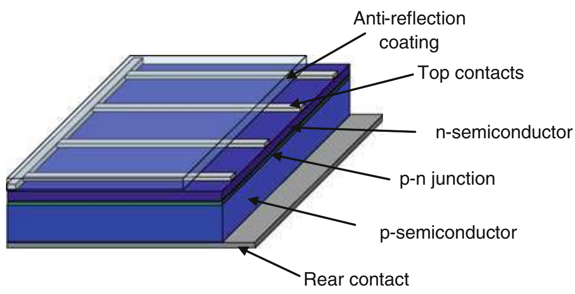


Fig. 3.21 Close up view of part of a single monocrystalline cell with 36 grid contact lines

3.4.2 Types of Photovoltaic Cell

There are many types of photovoltaic cells available and due to the increasing demand for renewable technologies, the manufacture of photovoltaic cells has advanced dramatically in recent years. The different cell types can be generally

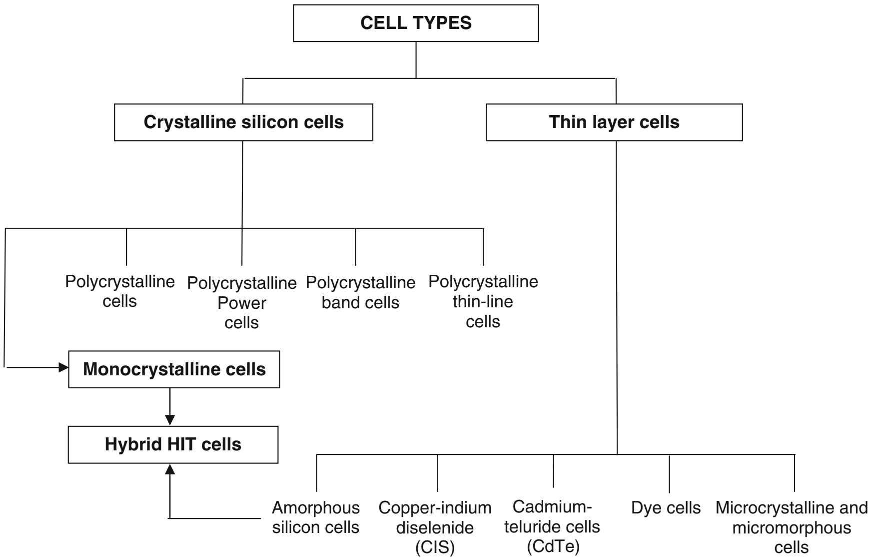


Fig. 3.22 Types of photovoltaic cells

classified according to the materials or fabrication process used in their manufacture. Figure 3.22 details many of the different types of PV cells available.

3.4.2.1 Crystalline Silicon Cells

Monocrystalline silicon cells: Until recently most PV cells were made from extremely pure monocrystalline silicon, i.e. silicon with a single continuous crystal lattice, as shown in earlier figures, with virtually no defects or impurities. Monocrystalline silicon is usually grown from a small crystal seed that is slowly pulled out of a molten mass of the less pure polycrystalline silicon. Several specific processes can be used to accomplish this. The most established and dependable means are the Czochralski method and the floating-zone (FZ) technique.

Polycrystalline silicon cells: Polycrystalline silicon consists of small randomly packed grains of monocrystalline silicon cast into single ingots. These ingots may be cut, using fine wire saws, into thin square wafers and these wafers formed into complete cells, in the same way as monocrystalline silicon cells. These square cells virtually eliminate any 'inactive' areas between cells when compared to circular cells. Polycrystalline silicon cells are easier and cheaper to manufacture than their monocrystalline silicon counterparts but they tend to be less efficient at around 10% (Fig. 3.23).

Each individual cell is interconnected to other cells to form a module at the desired electrical characteristics and the entire assembly encapsulated in a transparent insulating thermoplastic polymer. Ethylene vinyl acetate (EVA) is the most

Fig. 3.23 Typical monocrystalline cell (*left*) polycrystalline cell (*right*)

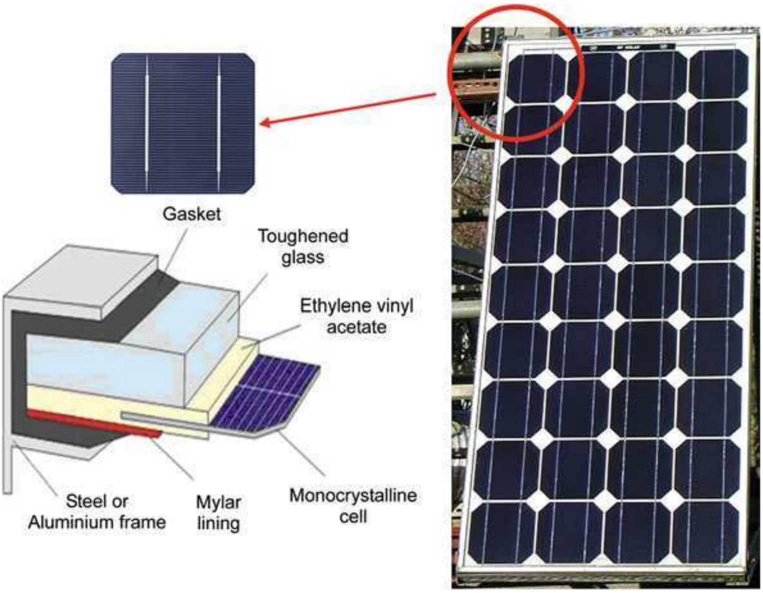


Fig. 3.24 Formation of individual silicon cells into PV module

widely used. The encapsulated cells and metal interconnectors are then typically sandwiched between a low-iron tempered glass sheet and a back cover made of Mylar foil. These layers are laminated by applying heat and pressure in a vacuum, with primers used to improve adhesion. Once finished, the laminate has a rubber gasket applied to the edges and is placed in an aluminium or steel mounting frame. Figure 3.24 illustrates a typical assembly detail.

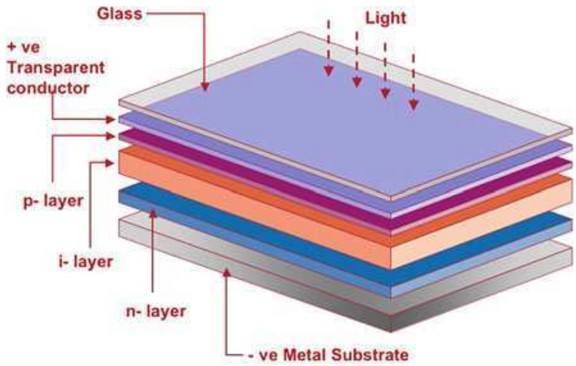


Fig. 3.25 Formation of a thin film amorphous silicon cell

3.4.2.2 Thin Film Cells

Crystalline silicon cells have to be individually interconnected into a module but thin film devices can be made monolithically i.e. as a large single unit. Layer upon layer is deposited sequentially on a glass or plastic substrate, from the anti-reflection coating and conducting oxide, to the semiconductor material and the back electrical contacts. Several different deposition techniques can be used including vapour deposition, sputtering or electrochemical deposition. Unlike most single-crystal cells, a typical thin film device does not use a metal grid for the top electrical contact. Instead, it uses a thin layer of a transparent conducting oxide (such as tin oxide). These oxides are highly transparent and good conductors of electricity. A separate anti-reflection coating may be used to finish the device. Alternatively, the transparent conducting oxide may also serve this function.

Silicon is not only capable of being formed into monocrystalline and poly-crystalline structures, it can also be made into a less structured form called amorphous silicon (a-Si) in which the silicon atoms are much less ordered than in the crystalline form. Typical amorphous silicon cells employ a p–i–n design in which an intrinsic layer is sandwiched between the ‘p’ layer and the ‘n’ layer. The unique properties of amorphous silicon allow cells to be designed with an ultra-thin (0.008 μm) p-type top layer, a thicker (0.5–1 μm) intrinsic (middle) layer, and a very thin (0.02 μm) n-type bottom layer. The top layer is made so thin and relatively transparent that most incident light passes straight through it, to generate free electrons in the intrinsic layer. The ‘p’ and ‘n’ layers (produced by doping amorphous silicon) create an electric field across the entire intrinsic region to induce electron movement in that layer (Figs. 3.25, 3.26).

Other materials such as Copper-indium diselenide (CIS) or Cadmium-teluride cells (CdTe) are also commonly used as semiconductor layers. Copper-indium diselenide is a compound of copper, indium and selenium and has an extremely high absorptivity that allows 99% of the available light to be absorbed in the first micron of the material. CIS modules also do not appear to suffer from the performance degradation observed in a-Si PV modules. Cadmium telluride (CdTe) is another

Fig. 3.26 Typical thin film cell

prominent polycrystalline thin film material which also has a very high absorptivity. Like CIS, CdTe films can be manufactured using low-cost techniques.

3.4.2.3 Hybrid Cells

The hybrid HIT cell is a combination of a crystalline and a thin film cell structures. A monocrystalline wafer is coated on both sides with a thin layer of amorphous silicon, creating a p–n junction between two differing structures (opposed to a p–n junction in conventional silicon cells where there is only one semiconductor material). The term HIT refers to the Hetrojunction with Intrinsic Thin layer. Compared to crystalline cells there is greater energy yields at higher temperatures, no deterioration of efficiency and savings in energy and material in production.

3.4.2.4 Concentration

Another way of increasing the power output of a PV cell is to concentrate the solar radiation onto the cell. In addition to increasing the power and reducing the size or number of cells used, concentrators have the additional advantage that cell efficiency increases under concentrated light. Increases in efficiency depend largely on the cell design and the cell material used. Another advantage of the concentrator is that it can use small individual cells. It is more difficult to produce high-efficiency cells in larger areas than it is to produce smaller area high-efficiency cells.

There are, however, several drawbacks to using concentrators. The concentrating systems are significantly more expensive than a simple flat cover needed for standard module and in addition, to be effective, the majority of concentrators must have a tracking capability. Thus, higher concentration ratios have increased costs and need much more precise controls than a stationary PV system.

High concentration ratios also increase the operating temperature of the cells due to the increased solar radiation energy. Cell efficiencies decrease as the

Fig. 3.27 PVT system with active cooling to maintain PV operating temperature with a maximum of 50°C

temperature increases and higher temperatures also threaten the long-term stability of PV cells. Therefore, PV cells must be kept cool. The main types of concentration configuration employ either parabolic trough or compound parabolic trough reflectors or fresnel lens concentrators. The parabolic trough concentrating PV(T) arrangement shown in Fig. 3.27 utilises water cooling to reduce cell temperatures, producing a hot water supply as a by-product.

3.4.3 The Photovoltaic System

Most photovoltaic systems cannot be described as being a PV module alone, many other components are necessary to provide an electrical supply (Fig. 3.28). Thus a complete solar PV system may consist of a number of parts or sub-parts:

- The PV module(s) and support structure, including tracking system if necessary.
- Storage system.
- Power regulation and control system, including monitoring.
- Auxiliary power systems.

The selection of components and size of any system is very much dependant upon a number of considerations. The basic photovoltaic power system can thus be generally classified according to:

- How it is connected to other power sources and electrical loads (stand-alone, grid connected or hybrid).
- Its functional and operational requirements (load requirement).
- Its component configurations (Balance Of System).

3.4.3.1 System Installation

Photovoltaic systems can either be stand-alone, grid connected or hybrid, with many combinations within these general headings possible. Figure 3.29 illustrates some of the common configurations.

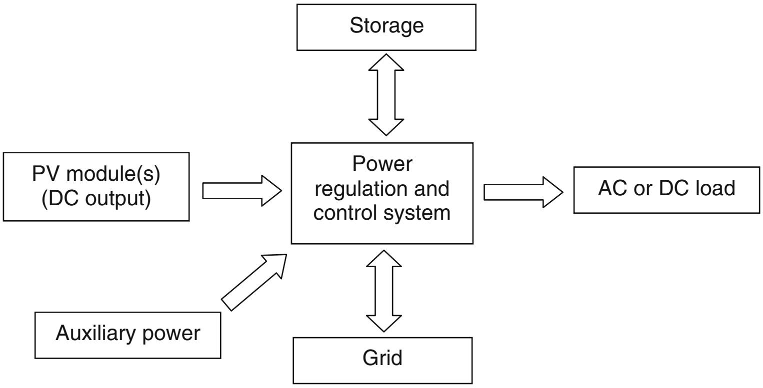


Fig. 3.28 The photovoltaic system

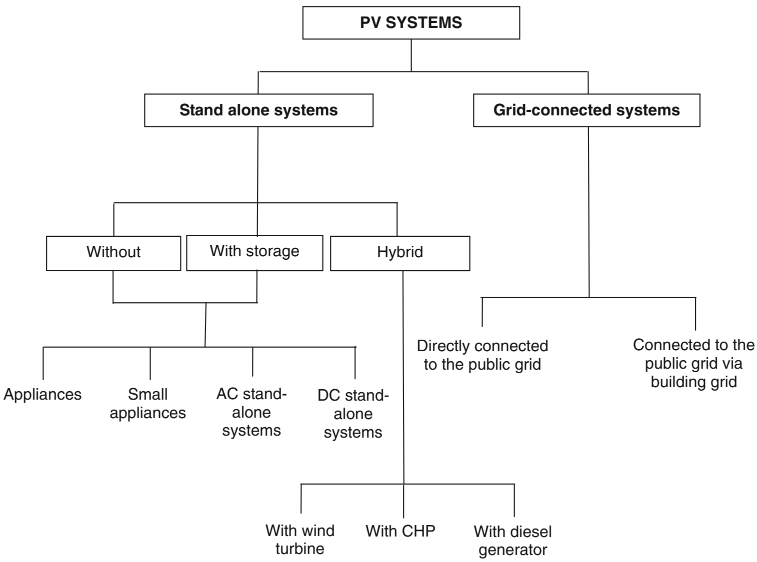


Fig. 3.29 Types of photovoltaic installation

Grid-connected systems: Grid-connected or utility-interactive PV systems are designed to operate in parallel with and interconnected to the electric utility grid (Fig. 3.30). Grid connected systems can vary in size from small domestic dwelling installations to large solar PV power stations.

Stand-alone systems: Stand-alone systems were examples of the first cost effective applications of photovoltaics. Stand-alone PV systems are designed to operate independently of the electric utility grid and are generally designed and

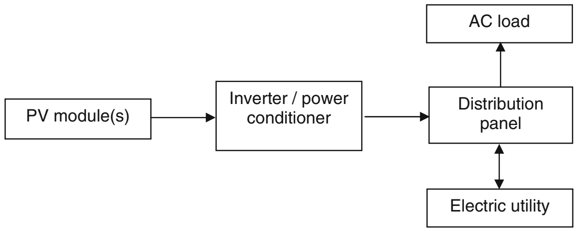


Fig. 3.30 Grid-connected PV supply

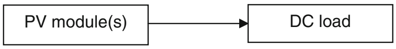


Fig. 3.31 Direct coupled stand-alone supply

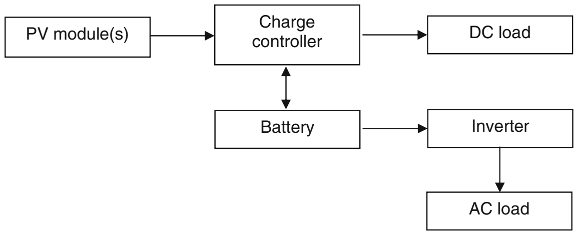


Fig. 3.32 Stand-alone AC/DC supply with storage

sized to supply certain DC and/or AC electrical loads. The simplest type of stand-alone PV system is a direct-coupled system (Fig. 3.31), where the DC output of a PV module or array is directly connected to a DC load. In many stand-alone PV systems, batteries are used for energy storage (Fig. 3.32).

Hybrid systems: A hybrid PV system is used to describe any power system with more than one type of generator, PV with a conventional generator or CHP and/or a renewable energy source such as a wind or hydroelectric turbine (Fig. 3.33).

3.4.3.2 Functional and Operational Requirements

The core of a PV system is the PV generator; module(s) interconnected to form a DC power producing unit. The performance of this PV system is very much dependant upon the operational performance of the modules under the localised operating conditions (Fig. 3.34).

The three most important electrical parameters of a PV module's operation are the short circuit current (I_{SC}), open circuit voltage (V_{OC}) and maximum power point (MPP or P_{MAX}) as functions of the local temperature and insolation. These three parameters can be used to generate the I–V curve of the PV.

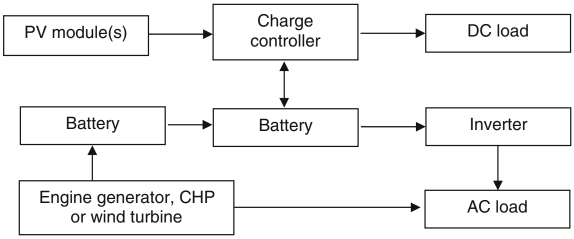


Fig. 3.33 Hybrid system

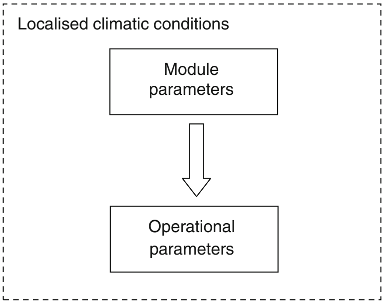


Fig. 3.34 The PV generator

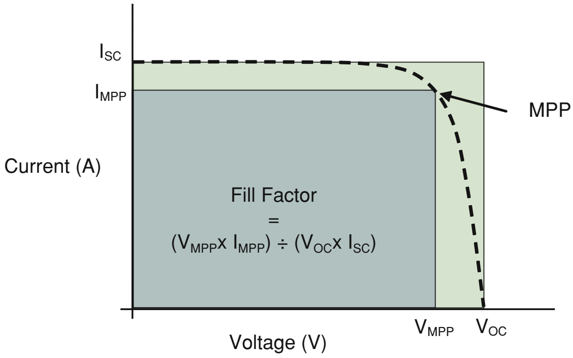


Fig. 3.35 Typical I–V characteristics for a PV cell, including Fill Factor

Module manufacturers will determine these electrical parameters at STC (Standard Test Conditions). Figure 3.35 shows the typical I–V characteristics for a PV cell.

The STC is used to compare PV modules with one another under uniform conditions, from which the I–V curve can be determined. The Standard Test Conditions relate to the IEC 60904/DIN EN 60904 standards.

- Vertical irradiance of 1,000 W/m^2.
- Cell temperature of 25°C.
- Defined solar spectrum at air mass 1.5.

In reality these conditions rarely occur and generally when the sun is shining, the cell temperature may exceed 25°C. It is therefore necessary to often specify the Nominal Operating Cell Temperature (NOCT) which is determined at an

Fig. 3.36 Series connection

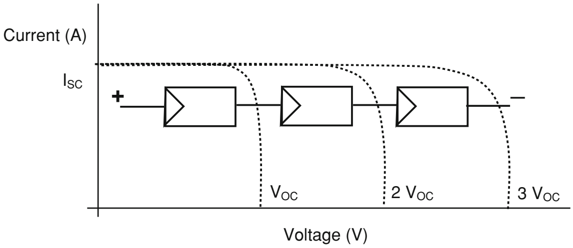
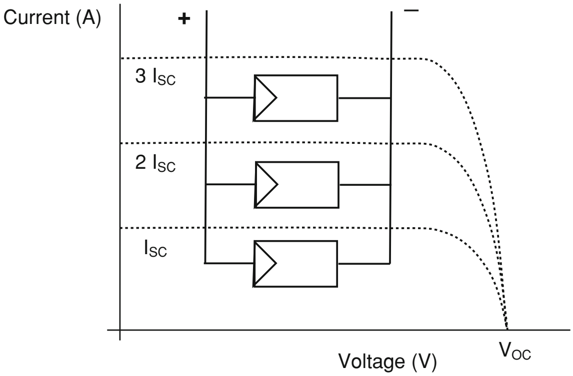


Fig. 3.37 Parallel connection



irradiance of 800 W/m^2, ambient temperature of 20°C and wind speed of 1 m/s. Another important parameter is the Fill Factor (FF) which describes the quality of a PV cell. It is defined as the quotient of the MPP and the theoretical maximum power which is a product of the short circuit current and open circuit voltage ($P_{MAX}/(I_{SC} \times V_{OC})$). When localised climatic conditions of temperature and insolation, along with FF, are accounted for, it is only then that we can determine the maximum power under actual operation.

A single PV module may be directly coupled, where the DC output of the module is directly connected to a DC load, however in many instances, a number of PV modules are combined in series or parallel to form an electrically larger unit, or mechanically to form an array. Series connected modules are described as a string. Figure 3.36 illustrates three modules connected in series to form a string along with resulting I–V curves. The number of modules in series determines the system voltage.

Parallel connections can be made with one module per string or several modules in multiple strings, as shown in Figs. 3.37 and 3.38, respectively.

When modules are connected together to operate as a unit, it is assumed that they all operate uniformly. However, differences in module quality and differing localised operating conditions may make it necessary to install by-pass diodes and string blocking diodes. When a module in a string (also cells in a module) is say shaded and is not producing electricity, it is converted into a diode under reverse

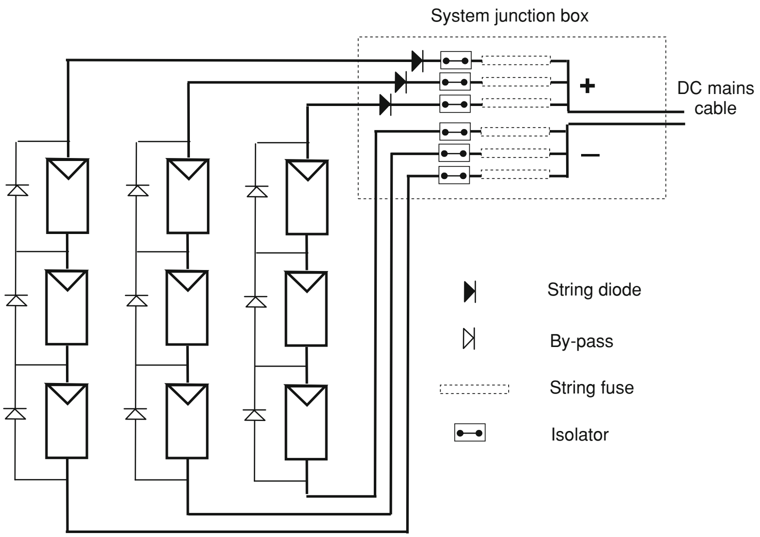


Fig. 3.38 PV system connections with protective devices and junction box (three modules per string and three strings in the array)

bias, eliminating current from the entire string and dissipating any power gain from the string. The by-pass diode limits the power dissipated and provides a low resistance path for the module current. The string 'blocking' diode performs a similar function, where individual strings can be decoupled if necessary. Problems, however, with faulty string diodes have meant that grid-connected systems tend to be installed without string diodes. Good design practice using the same PV module throughout, adhering to the standards of Protection Class II, means that the string diodes are not necessary in most modern installations.

3.4.3.3 Component Configurations

At the heart of a complete PV system is the PV module, but PV modules are only part of the system. All the additional equipment that forms a PV system is referred to as the Balance Of System (BOS) components, and may include;

- Regulators and charge controllers.
- Inverters.
- Batteries, racks, boxes and enclosures.
- Cables, connectors and junctions.
- Mounting structures.

The selection of the correct BOS components is very much dependant on the type of system, whether it is grid connected or stand alone.

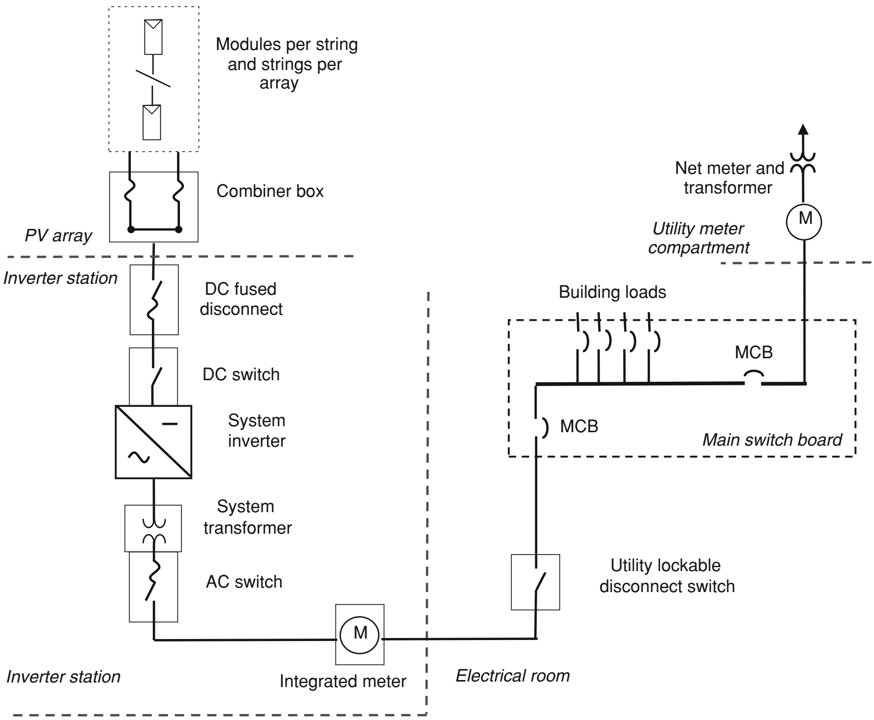


Fig. 3.39 A schematic diagram of a simple PV system and building load connection

Grid Connected System BOS

Grid connected systems can differ in many ways. The majority of systems however, will have (in addition to the modules) cabling with appropriate connections, system inverter(s), AC and DC switching devices and monitoring equipment. Figure 3.39 schematically illustrates a simple grid connected installation.

Cabling and Connection Systems: In terms of any PV installation, a distinction should be made for wiring/cable between module or string cables and DC main cable and AC connection cable. From the module junction box, the positive and negative conductors for module and/or string cables are kept separate for earthing reasons and single, double insulated cables, for outdoor operation are generally preferred. These ‘solar’ cables must also be capable of withstanding high temperatures and be UV resistant. String cable and other DC cable connections can be connected via screw terminals, post terminals, spring clamp terminals or plug connectors. Most connections will be housed in a combiner box. Combiner boxes come in a wide variety of forms, a typical box will receive up to 12 cables (1.5–6 mm^2) depending upon the system size. As they are normally located outside, they must be able to withstand the local weather and environmental conditions.

Fig. 3.40 Building grid connected inverter with isolation devices and cabling/ connections

The main DC cable connects the junction/combiner box to the inverter. As previously mentioned with DC cabling, single wired sheathed cables are preferred, with appropriate protection from local environmental conditions and mechanical damage. The AC connection cable links the inverter to the main electricity grid. National electrical codes and regulations must be followed to ensure correct selection of the AC cable for either single or three phase supply.

Grid Connected Inverters: The most important BOS component in a grid connected system is undoubtedly the inverter, sometimes referred to as a DC/AC convertor (converting PV Direct Current electricity into Alternating Current electricity). The inverter is the link between the PV generator and the AC grid and loads. Grid connected inverters must not be confused with inverters in stand-alone systems (Fig. 3.40).

In grid connected systems, the inverter is generally linked in one of two ways; directly where any generated power is fed only into the mains electrical grid or indirectly via the building's grid where the generated power is used firstly in the building and any surplus power is fed into the mains electrical grid. Small PV systems (less than 5 kWp) are generally single phase connections, whilst bigger PV systems can be three phase connections.

To maximise solar generated power, the inverter must work at the MPP of the PV generator but as the power produced varies with localised conditions, an MPP tractor within the inverter ensures that maximum power is always being supplied. The MPP tractor is in essence a DC/DC converter which adjusts the inverter to maintain optimal output.

The majority of inverters can be classified according to their operation. In older systems the inverter was a bridge circuit with thyristors. The grid controlled inverter uses the mains voltage to determine the switch-on and switch-off actions. Each thyristor in the bridge switching the DC power in one direction and then the other forming rather 'square' wave currents, giving significant deviation from the

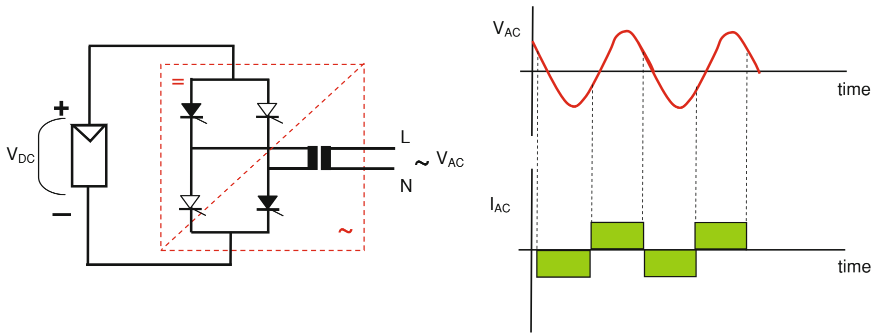


Fig. 3.41 Principle of a thyristor based grid controlled inverter

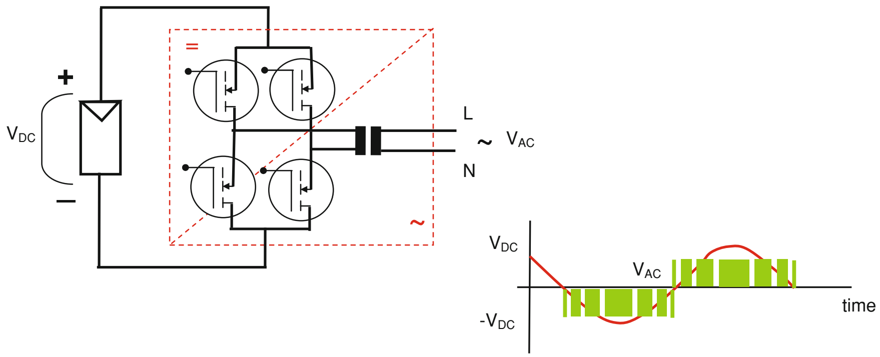


Fig. 3.42 Principle of a self-commutating inverter

mains power sine wave currents, leading to high harmonic disturbances and reactive power issues. Self-commutating fixed frequency inverters utilise semi-conductor devices in the bridge circuit and through rapid switching on and off at various frequencies, pulses are formed. This pulse width modulation offers a more representative mains sinusoidal wave. Self-commutating fixed frequency inverters are able to feed an isolated distribution grid and, with special paralleling control, a grid supplied by other parallel power sources. Line-commutating fixed frequency inverters are able to feed the grid only where the grid frequency is defined by another power source connected in parallel (Figs. 3.41, 3.42).

As previously mentioned, to maximise system efficiency, inverters should be optimally adjusted to the PV modules, with every module operating continually at its MPP. This is the principle of the micro or module inverter concept, were each module has its own inverter and are sometimes referred to as AC modules. Apart from improved module output, due to each module operating in stand-alone mode, this arrangement is also advantageous in locations were partial shading is a problem or as part of a system which may be extended some time in the future.

On the downside, module inverters still remain relatively expensive and are therefore still quite rare.

AC and DC switching device: To enable faults to be isolated or maintenance and repair work to be carried out, it is necessary to have devices that can isolate the solar installation. This is the DC main switch on the DC side of the inverter. The switch should have a load switching capability and be rated to the open circuit voltage of the PV installation and its maximum generated current. In larger installations, the DC main switch should be located beside the inverter(s). The AC switch disconnector must be double pole and lockable in the off position with clear labelling. In most installations a second isolator will be present, one of which is located beside the inverter.

Stand Alone System BOS

As previously stated, the simplest type of stand-alone PV system is a direct-coupled system, where the DC output of a PV module or array is directly connected to a DC load. However, for many stand-alone PV systems, storage is required and thus the principle components of the BOS are batteries and charge controller and, where an AC load is present, a stand alone inverter.

Charge regulator/controller: For PV stand alone systems with battery storage, a the PV array voltage should be matched to that of the battery, typically 12, 24 or 48 V, with the charge voltage slightly higher and the system nominal voltage slightly higher again to account for moving MPP voltage and cable/device voltage loss. The charge controller also measures the battery voltage and protects it from overcharging. At low or no collection conditions, a reverse current diode is integrated into the charge controller to prevent the battery discharging into the PV array. Flexibility is often necessary within charge controller operation to account for different battery types and battery temperature and age so that optimal battery operation is assured. There are three main forms of charge controller; series, shunt (parallel) and MPP charge controller. Series charge controllers switch in and out (using relays), depending upon the battery charge, creating an oscillating switching action. The shunt charge controller continuously reduces the module(s) power when the cut-out voltage is reached, with the unneeded portion of the generated power dissipated as heat at the module(s) (as a short circuit current). Both of these controllers, however, do not always utilise the maximum available solar energy, losing anywhere between 10 and 40% based on battery voltage, solar radiation and temperature. This, however is overcome by using a MPP charge controller, which using a regulated DC/DC converter, tracks the current/voltage characteristic curve of the PV array for the optimal MPP output and adjusts it to the charge voltage of the battery.

Batteries: Energy storage is necessary in most stand-alone PV applications as there is often a mismatch between generation and load. The most common form of battery type found in stand alone PV systems is the rechargeable lead acid

battery, primarily due to cost effectiveness and their high efficiency in dealing with a range of charging currents. Lead acid batteries can be grouped as either deep cycle or shallow cycle. Shallow cycle batteries, like those used in starting an engine, are designed to supply a large amount of current for a short time and to stand mild overcharge without losing electrolyte. They cannot tolerate being deeply discharged and if they are repeatedly discharged their life will be very short. Deep cycle batteries are designed to be repeatedly discharged by as much as 80% of their capacity and are thus ideal for energy storage in PV systems.

Stand alone inverter: In some instances, an AC load may be required in tandem with DC loads, realised through a stand alone PV installation with battery storage. Three different inverters exist for stand alone operation; sine wave, modified sine wave and square sine wave.

3.5 Solar Thermal (Heating and Power)

3.5.1 Solar System Classification

A solar thermal system is distinctly different from passive solar design, in that a specific system is utilised to capture useful solar energy. However, under this wide umbrella term, there are many ways in which these systems can be classified. In this context they can be grouped as stand-alone or solar-augmented, active or passive, liquid or air, thermal storage and collector type.

3.5.1.1 Solar Stand-Alone or Solar-Augmented

A solar system may be classified as being stand-alone if the energy being supplied from the solar system is the only source of energy being supplied. Typically these systems would be designed for applications where it is not necessary for the solar input to always meet the specified demand. This type of supply is generally acceptable in certain applications, such as solar desalination or crop drying.

Solar-augmented systems apply to systems where the solar input meets all or a portion of the demand with any shortfall being met by an auxiliary source. In such installations, the auxiliary system is sized to supply all of the demand but the solar system is given priority and thus displacing any of the conventional energy source required. Solar-augmented systems are widely used and form the majority of solar systems installed for building and process applications.

3.5.1.2 Solar Active or Passive

A passive solar thermal system is a system that collects and distributes solar energy without using an external source of energy, such as electricity. Typical

systems in this range include natural thermosyphonic collectors that transfer a heated medium from the collector to the store or load. Active solar systems require an externally powered device such as a pump or fan to transfer the heated medium from the collector to the store or load.

3.5.1.3 Solar Liquid or Air

Solar air systems, where air is the primary heat medium, are typically used in space heating or drying applications. Due to the wider application of liquid based systems, solar air collectors are not as widespread. The basic principles and concepts for solar collection remain the same as liquid based system but there are significant differences in design, construction, configuration and operation.

There are many variations to the liquid based system, some of which are discussed in greater detail in following sections, but most can be classified according to their range of operating temperature or thermal production. Low grade thermal systems operating in temperature ranges less than 100°C tend to be less costly to install, operate and maintain and usually operate at higher efficiency when a lower temperature supply is required. Higher grade systems usually require solar concentration and tend to require more auxiliary infrastructure and control, leading to increased costs and complexity.

3.5.1.4 Solar Thermal Storage

Thermal energy storage is required when there is a mismatch in time between the heat generation and heat demand or when a certain quantity of heat is required that cannot be obtained instantaneously from the available energy sources. The major factors that influence the designs for thermal energy stores are:

- *Storage medium*: Thermal energy can be stored in the form of sensible heat through a solid or liquid medium, a latent form in a phase change material or through a reversible chemical reaction of two or more substances.
- *Temperature*: The temperature required in storage, ranging from those required in cooling applications to power generation.
- *The volume of space available*: The energy density obtainable in a store is a function of the storage material density, its specific heat capacity and, if phase change materials are involved, its latent heat capacity.
- *Heat transfer into the store*: If the rate of heat transfer into a store is low, charging times will be long. If the efficiency of heat transfer is low, then total system efficiency will be reduced due to increased heat loss to ambient.
- *Heat transfer from the store to the load*: The heat transfer from the store should be such that it can efficiently meet the required load profile.
- *Duration*: The desired duration of storage, typically daily or seasonal. Daily storage relates to the storage of solar energy for at most a few days of the related heating load

taking the day to day climatic fluctuations into account. Seasonal storage relates to the storage of heat over an extended period lasting up to weeks or months, typically collecting during the summer months for use in the colder winter months.

- *Parasitic heat loss from the store*: Heat loss from the store over the duration of storage represents a reduction in that which is available to the load.
- *Degradation of energy quality*: Maintaining good thermal stratification within the store ensures maximum delivery temperature to the load. Mixing of hot and cold materials within the store reduces the delivery temperature.

3.5.1.5 Solar Collector System

For any active solar system the most important, and certainly most visual, component is the collector. All active solar collectors are either stationary or tracking and both forms can be further identified according to their absorber type (flat, tubular or point absorbers), concentration ratio, indicative temperatures and application. Tables 3.1 and 3.2 describe a taxonomy of the most common generic solar thermal collectors using these different primary characteristics.

3.5.2 Solar Water Heating

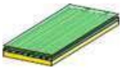
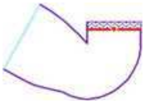
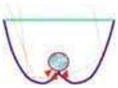
Solar water heaters for 'domestic' water heating applications can provide users with a large proportion of their hot water needs while reducing the amount of conventional fuel used and hence reducing energy costs. The amount of hot water produced will depend upon the type and size of the system, the climate and location in terms of solar access. Over the years, a variety of system designs have been developed and tested to meet specific consumer needs and environmental conditions.

Solar water heaters can be categorised as being either active or passive and can be further grouped according to the configuration of the main solar water heating components; integral or distributed. Integrated systems combine the collector and storage functions in a single unit, whilst distributed systems have a separate solar collector and hot water store connected by a piping network. Distributed systems can be either active or passive. In active systems, a pump is used to circulate the transfer fluid between the collector and store. Integrated systems are almost always passive as they do not require external power.

3.5.2.1 The Integrated Collector/Storage Solar Water Heater

The most basic of solar water heaters is the Integrated Collector/Storage Solar Water Heating (ICSSWH) system or Integral Passive Solar Water Heater (IPSWH), commonly referred to as breadbox or batch water heaters. Kemp's early Climax Solar-Water Heater was an integrated system, as detailed in Sect. 3.1.

Table 3.1 Stationary (Non-tracking) Solar thermal energy collectors [6]

Collector type		Absorber type			Concentration ratio for direct insolation "C"	Indicative temperatures obtained T(K)	Applications
Name	Schematic	Flat	Tabular	Point			
Non-convecting solar pond		√			$C \leq 1$	300–600	Power generation, process heat
Flat-plate absorber		√			$C \leq 1$	300–350	Hot water/air photocatalytic decontamniation
Inverted absorber compound parabolic reflector		√			$1 \leq C < 3$	320–430	Hot water and process heat
Evacuated envelope		√			$C \leq 1$	320–460	Hot water and active solar cooling
Compound parabolic reflector			√		$1 \leq C < 5$	340–510	Process heat

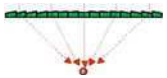
In its simplest form the ICSSWH is a water tank painted black to absorb incident solar radiation. Variations consist of one or more tanks, painted black or coated with a selective absorbing surface, within a well insulated box, possibly with reflectors and covered with single, double or even triple layers of glass, plastic or a combination of the two. Due to its simplicity, an integrated collector/storage system is easier to construct and install which reduces maintenance and capital costs. In most climates, the large thermal mass of the store provides inherent resistance to freezing. However the integrated unit has a significant problem due to its unique mode of operation (Fig. 3.43).

The earliest systems suffered substantially from heat losses to ambient, especially at night-time and non-collection periods. This meant no matter how effective the unit was in collecting solar energy, unless the hot water was fully withdrawn at the end of the collection period, losses to ambient led to only luke warm water being available early the next day. This reduced the overall solar fraction rendering it less viable economically. Indeed this deficiency in the late nineteenth century led to the prominence of thermosyphon solar water heaters with diurnal heat storage to the detriment of the ICSSWH system. To overcome excessive heat loss and be in a position to compete with the more established distributed solar water heater systems, the ICSSWH design has had to evolve and incorporate new and novel methods of improving performance.

3.5.2.2 Distributed Solar Water Heaters

Distributed systems consist of a separate solar collector and water store, with pipes connecting the collector(s) to and from store(s). As previously mentioned, these

Table 3.2 Tracking solar thermal energy collectors [6]

Collector type		Tracking	Absorber Type		Concentration ratio for direct insolation "C"	Indicative temparatures T(K)	Applications[a]
Name	Schematic		Tube	Pt			
Compound parabolic reflector		Single axis	√		$5 \le C \le 15$	340–560	Process heat
Parabolic reflector		Single axis	√		$15 < C < 40$	340–560	
Fresnel refractor		Single axis	√		$10 < C < 40$	340–540	
Parabolic dish reflector		Two axes		√	$100 < C < 1000$	340–1200	Photolytic decontamination
Heliostat field		Two axes		√	$100 < C < 1500$	400–3000	Process heat

[a] All tracking system have the capacity for electricity generation

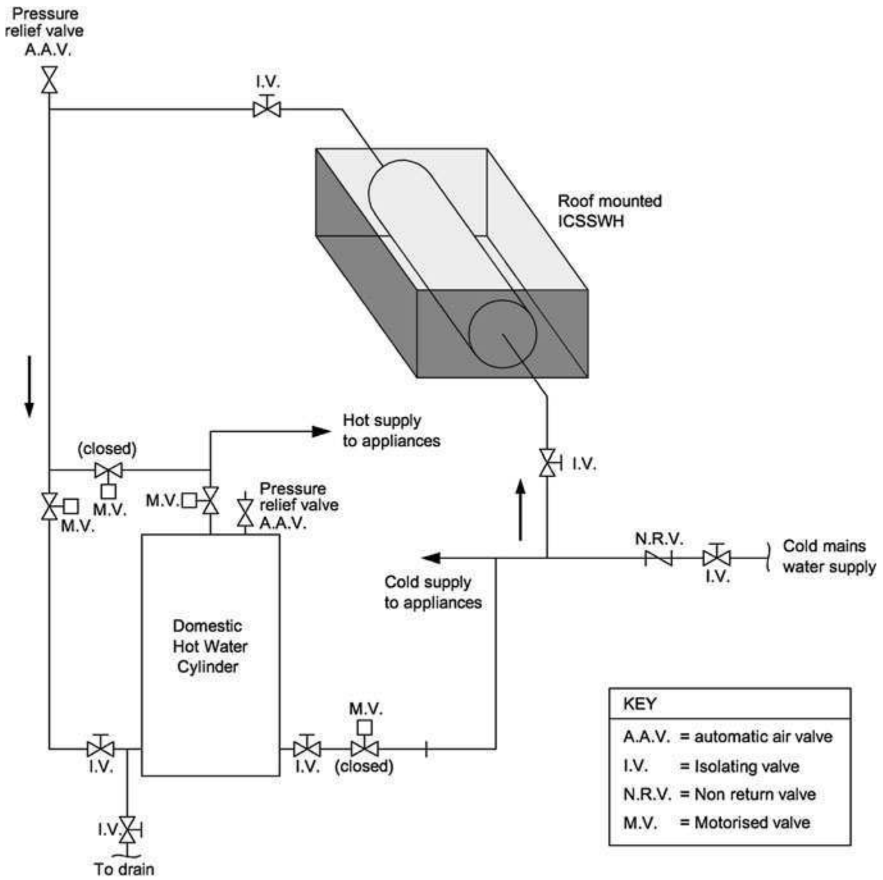


Fig. 3.43 A simplified diagram of a typical roof mounted ICS solar water heating installation

systems can be either active or passive, with the active system using an electric pump, and the passive system relying on buoyancy forces in the form of thermosiphonic action. Active systems also require more valves and control systems, which tend to make them more expensive than passive systems but generally more efficient. Figure 3.44 shows a simplified diagram of a typical roof mounted distributed (flat plate) solar water heating installation. Active systems are often easier to retrofit than passive systems because their storage vessels do not need to be installed above or close to the collectors. In addition, a photovoltaic panel could be used to power the pump, resulting in stand alone, proportional pump operation with reduced running costs.

Distributed solar water heaters can also be characterised as being direct (open loop) or indirect (closed loop). A direct system circulates incoming mains water through the collector and into the tank, whilst an indirect system transfers collected

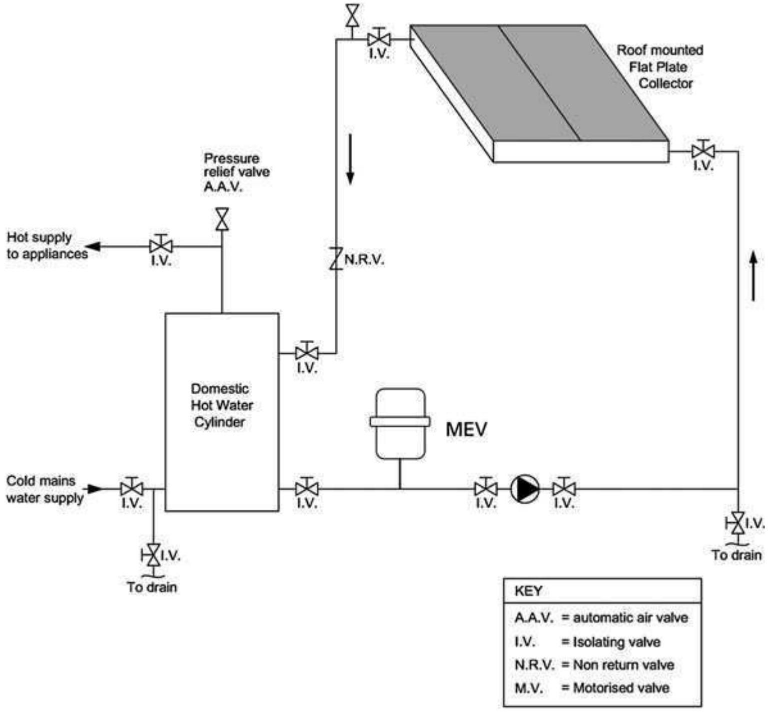


Fig. 3.44 A simplified diagram of a typical roof mounted distributed (flat plate) solar water heating installation

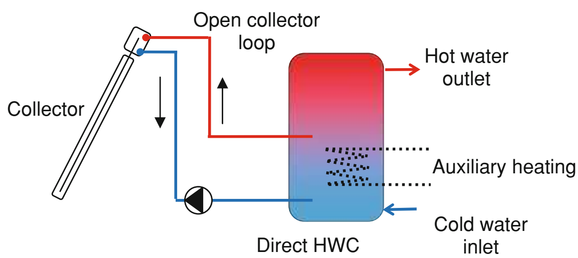


Fig. 3.45 A simplified schematic diagram of an active direct system distributed solar water heating configuration

thermal energy via a heat exchanger to the domestic water. Indirect systems usually contain an aqueous anti-freeze solution that flows through the heat exchanger immersed in the hot water store to provide protection from freezing. This, however, results in reduced collection efficiencies over the direct system through lower specific heat capacities and losses during the heat exchange process.

Active Direct Systems: Active direct systems use pumps to circulate incoming mains water through the collector and back into the tank. This design is efficient and reduces operating costs but is not appropriate where water is hard or acidic because of scale build-up and corrosion. However, direct active systems are popular in regions that do not experience freezing temperatures (Fig. 3.45).

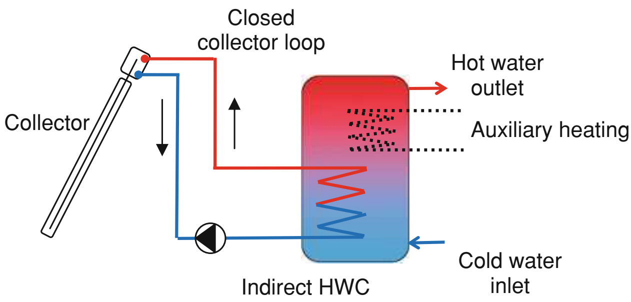


Fig. 3.46 A simplified schematic diagram of a common active indirect distributed solar water heating configuration

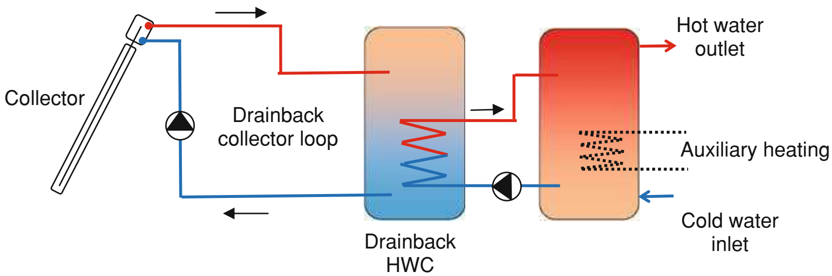


Fig. 3.47 A simplified schematic diagram of an indirect drainback distributed solar water heating configuration

Active Indirect Systems: Active indirect systems pump the heat-transfer fluid (usually a glycol–water anti-freeze mixture) through the collector and a heat exchanger transfers the heat from the fluid to the water that is stored in the tank. Heat exchangers can be double-walled vessels or have twin coil arrangements. Indirect glycol systems are popular in areas where temperatures regularly fall below zero because they offer good protection from freezing. However, anti-freeze systems are more expensive to purchase and install and require regular checking and maintenance (Fig. 3.46).

Indirect Drainback Systems: Indirect drainback systems do not use anti-freeze mixtures, but use pumped water as the heat-transfer fluid in the collector loop. When freezing conditions prevail or the system is not in use, the pump is switched off and the water in the collector is drained out thus providing protection from freezing. The collector installation and plumbing arrangement must be carefully positioned to allow complete drainage and the pump must have sufficient head pressure to pump the water up to the collector each time the pump starts (Fig. 3.47).

Thermosiphon Systems: A thermosiphon system relies on warm water rising, a phenomenon known as natural convection or buoyancy to circulate water to and from the collector and tank. In this type of installation the tank must be located above the collector. As water in the collector heats, it becomes less dense and

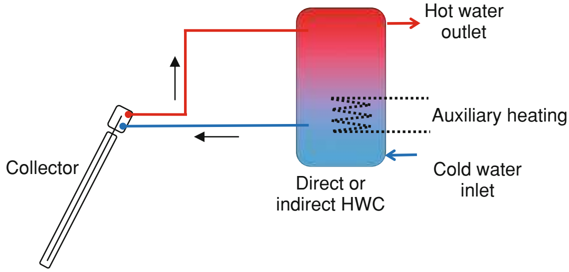


Fig. 3.48 A simplified schematic diagram of a thermosiphon direct distributed solar water heating configuration

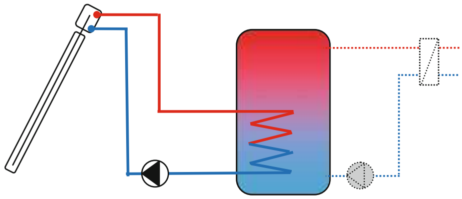


Fig. 3.49 A simplified schematic diagram of an active indirect system with internal heat exchanger (*note* in this diagram the hot water outlet is via an external heat exchanger)

naturally rises into the tank above. Meanwhile, cooler water in the tank flows downwards into the collector, thus causing circulation throughout the system. Some forms of thermosiphon solar water heaters can be described as being compact. Compact systems are close coupled thermosyphon flat plate or evacuated tube collector units fabricated and installed as a single item as opposed to a separate collector, store and pipework. Thermosiphon systems are much cheaper than active systems as no pump or controller is required and are ideal where a low cost solar heater is required such as holiday houses and cabins, or countries where low cost solar heating is required (Fig. 3.48).

The previous diagrams detail some of the generic distributed solar water heating configurations commonly used in small scale domestic hot water applications. In larger commercial scale solar water heating (both DHW and space heating) applications, the vast majority of installations utilise an active indirect distributed format. There are, however, many variations to this configuration in common operation, which vary according to the number of tanks used, the method of thermal store discharge, auxiliary heat input or the location of the heat exchanger.

Single tank configurations: The most basic active indirect format uses an internal heat exchanger which comprises a finned or plain tube coil located at the base of the store (Fig. 3.49) (*Note* no auxiliary thermal input shown). Thermal conduction of heat from the coil to the domestic store creates convective movement in which heated water rises to the upper portion of the tank.

In larger installations it is sometimes common to install a three-way valve in the collector loop to create a by-pass circuit. A sensor measures solar radiation incident upon the collector and when a threshold value is achieved the pump is activated and the collector circuit fluid flows through the collector and is heated.

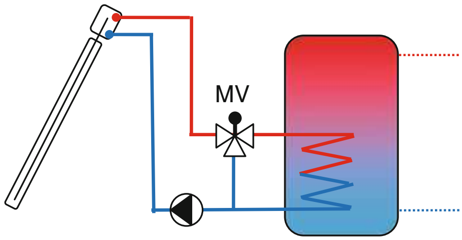


Fig. 3.50 A simplified schematic diagram of an active indirect system with by-pass circuit and simple direct cold water inlet and hot water outlet

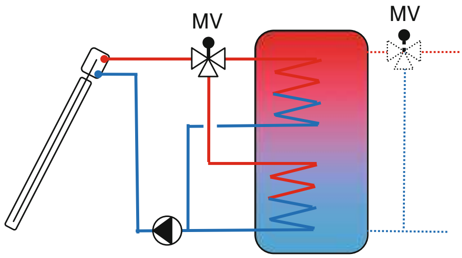


Fig. 3.51 A simplified schematic diagram of an active indirect system with a stratified charging arrangement and by-pass on the cold water inlet and hot water outlet circuit

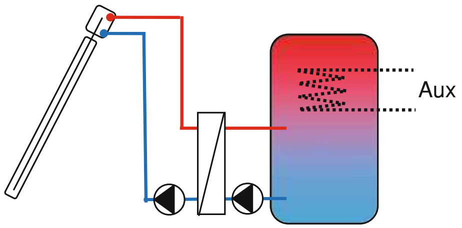


Fig. 3.52 A simplified schematic diagram of an active indirect system with external heat exchanger

Once a suitable fluid temperature is attained, the three-way valve opens to permit fluid to enter the heat exchanger, transferring solar collected energy to the store. A stratified charging arrangement with two internal heat exchangers (one at the top and one at the base of the store), combined with a three-way valve offers greater stratification within the store (Figs. 3.50, 3.51).

In some situations, when replacement of an existing single coil cylinder is not an option, retrofit heat exchangers coils can be used as an alternative. In these particular cases a slim in-line coil can be inserted into the hot water cylinder's immersion socket, connected directly to the solar collector circuit, providing a simple internal heat exchanger. For many larger water heating applications, external heat exchangers are used between the collector and store. A collector (primary) circuit flows through the heat exchanger, transferring heat to a secondary circuit which directly charges the store (Fig. 3.52). Typically, external heat exchangers provide better heat transfer properties over the internal counterpart. Figure 3.53 depicts two different external heat exchanger formats used in solar thermal installations.

Fig. 3.53 Different external solar system heat exchangers; Tubular Solasyphon heat exchanger (*left*) and plate heat exchanger (*right*)

The tank configuration can have a significant influence on the performance of the solar system. Coupled with the need to provide hot water for the user, whilst adhering to local water regulations on storage temperatures, the distribution of heat within tanks must be carefully considered. Thermal disinfection, due to issues such as legionella, is a necessary process within any hot water store. Periodic heating of the entire store to temperatures in excess of 60°C is required to kill off harmful pathogens and if the solar resource is not sufficient to attain these temperatures, auxiliary heat input must be used instead. This of course can have a detrimental effect on the solar collection potential of the system and it is for this reason that many tank configurations and heating strategies have been developed. Whilst any auxiliary heating for disinfection reasons is best performed in late afternoon, before any significant draw-off, the introduction of a pre-heat or buffer vessel before the main storage tank can improve the overall system performance.

Double tank configurations: Double/twin or buffer tank arrangements are a common feature of many solar hot water installations to improve system performance. Increased storage temperatures leads to higher heat loss from the store and connected system. In addition, a higher collector fluid inlet temperature (resulting from a high tank storage temperature) can reduce the collection efficiency of the collector, leading to reduced solar energy collection, in some cases up to 15% less. Therefore, the addition of a second tank can be advantageous to collection performance, against a small increase in the overall capital cost of the installation. The following section details a range of common double tank arrangements.

The simplest twin tank arrangement consists of an active indirect buffer store with a direct supply to the main storage tank (Fig. 3.54). Solar collected energy is transferred via the solar circuit to the internal heat exchanger in the buffer tank. When water is drawn from the main tank, it is replenished with solar heated water from the top of the buffer tank, which is in turn replenished with water from the cold feed at the base of the tank. Auxiliary heating exists in the main tank to provide top-up heating. A variation to this set up is shown in Fig. 3.55. In this

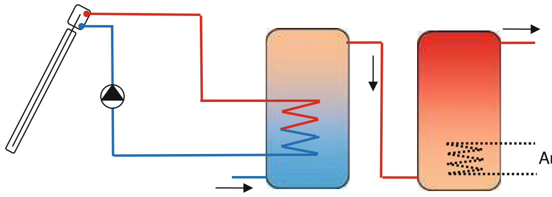


Fig. 3.54 A simplified schematic diagram of an active indirect twin store system with internal heat exchanger in the buffer tank and direct supply to the main store

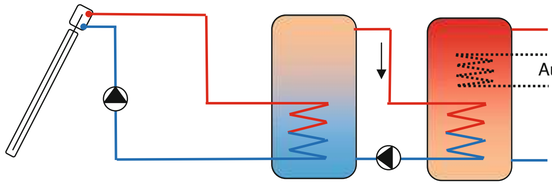


Fig. 3.55 A simplified schematic diagram of an active indirect twin store system with internal external heat exchangers in the buffer and main storage tanks

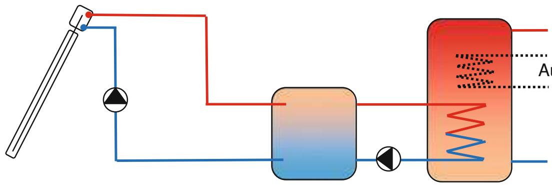


Fig. 3.56 A simplified schematic diagram of an active direct glycol buffer tank with an active indirect connection to the main storage tank

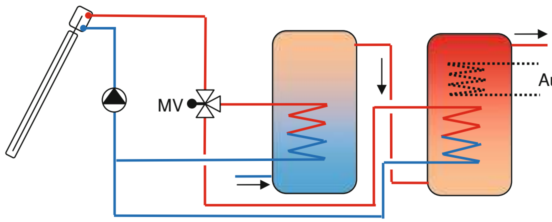


Fig. 3.57 A simplified schematic diagram of an active indirect (twin tank) cascade system with internal heat exchangers

example, the buffer tank is connected to the main tank via an active indirect (closed) circuit with heat transfer taking place through an internal heat exchanger. Hot water drawn from the main tank is directly replenished from a cold feed entering from the base. Rather than have an intermediate water filled buffer tank, a glycol buffer tank is sometimes used instead (Fig. 3.56).

The active indirect cascade twin tank arrangement with internal heat exchangers, shown in Fig. 3.57, allows both tanks to be charged with solar energy. If priority is given to draw-off, the main tank is charged first, but if the main tank is already heated, then the solar circuit is diverted to the pre-heat tank, with the main

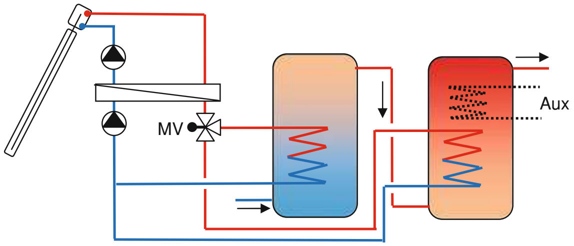


Fig. 3.58 A simplified schematic diagram of an active indirect cascade (twin tank) system with external heat exchanger on the collector circuit

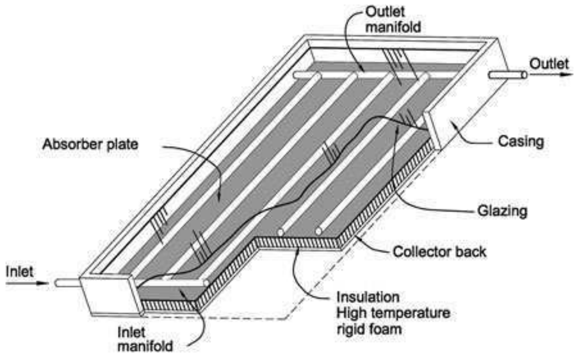


Fig. 3.59 A typical flat plate solar collector

tank receiving top-up heat when necessary. A variation to this arrangement is shown in Fig. 3.58, where an external heat exchanger is used between the stores and solar circuit.

3.5.2.3 Solar Water Heating Collectors

There are basically three types of domestic solar collector in common use today for water heating applications; flat plate, evacuated tube and concentrating.

Flat plate solar collector: The flat plate system consists of a 'flat' absorber panel through which water or conducting fluid passes. The panel may be of formed channels in a sandwich format or may be pipes connected to expanded absorber plates. Most absorbers are covered with a selective coating to improve solar radiation absorption and reduce long-wave radiative heat loss. As the fluid flows adjacent to the hot surface it is heated. The absorber is mounted in an insulated, weatherproof unit and the exposed collector aperture is covered with one or more transparent or translucent covers. The make-up of a typical flat plate solar collector is shown in Figs. 3.59 and 3.60.

Evacuated Tube Collector: Evacuated tube collectors are made up of rows of parallel, glass tubes linked to a common flow (and return) manifold depending on

Fig. 3.60 Flat plate solar collectors installed on a roof

the collector installed. There are two main operating formats for evacuated tube collectors, either a direct flow through operation or utilising a heat pipe. In addition, there are two fabrication configurations of evacuated tube collector; glass/glass or metal/glass. The glass/glass collector consists of two concentric glass tubes. The inner tube is covered with a selective coating to improve solar radiation absorption and reduce long-wave radiative heat loss. The transparent outer tube forms a space between the two tubes that is evacuated to eliminate conductive and convective heat loss. The metal/glass collector consists of a copper plate attached to a heat pipe or direct flow water pipe mounted within a single evacuated glass tube. Again the absorber is coated with a selective coating to improve the collection performance. Figure 3.61 shows images of the two types of evacuated tube collector; glass/glass or metal/glass whilst Fig. 3.62 illustrates a metal/glass heat pipe evacuated-tube solar collector with wet manifold and Fig. 3.63 shows a metal/glass water pipe evacuated tube solar collector.

As previously mentioned, there are two main operating formats for evacuated tube collectors; direct flow through or heat pipe. In the direct flow through design, the heat transfer fluid flows through a coaxial tube format (tube within a tube) or U tube format, whereupon the heat transfer fluid is in direct contact with the absorbing surface and is fully enclosed within the evacuated glass tube. The individual tubes are connected in parallel to a flow and return header manifold (Fig. 3.63) which connects the solar collection circuit to the store. The heat pipe collector combines the principles of both thermal conductivity and phase change to transfer solar collected heat to the collector heat transfer fluid. Typically, a selectively coated absorber strip is bonded to a sealed heat pipe tube. The heat pipe contains a working fluid (liquid) at a very low pressure. When the heat pipe is heated, the liquid turns into a vapour, rises within the pipe to a condenser that is in contact with the heat transfer fluid in the manifold. At the condenser the vapour condenses back into a liquid, releasing the latent heat. The liquid then returns back down the heat pipe where it is heated, evaporates and once more repeats the cycle.

In an evacuated heat pipe collector, the condenser is directly or indirectly (wet or dry) connected with the heat transfer fluid within the solar collection circuit.

Fig. 3.61 Two types of evacuated tube collector; metal/glass (heat pipe) and glass/glass

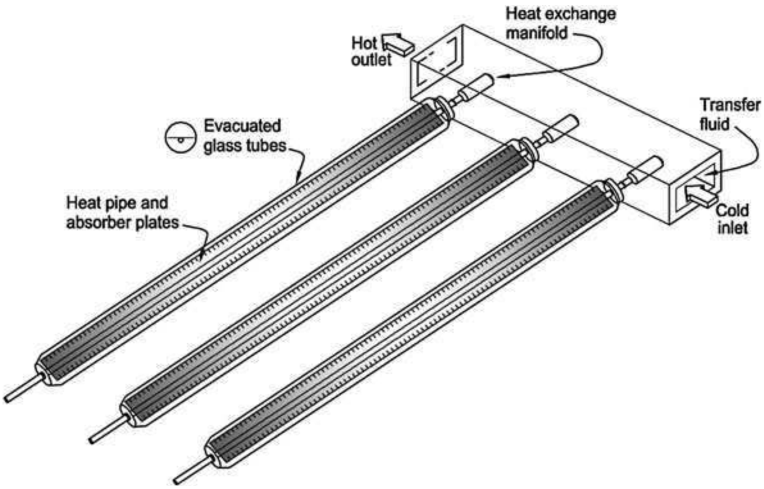


Fig. 3.62 Metal/glass heat pipe evacuated tube solar collector

Figure 3.62 illustrates a wet manifold format, where the heat pipe condenser is inserted into the manifold socket and is completely immersed in the heat transfer fluid flow path. If a tube needs to be replaced, the collector (and thus manifold) must be drained. In a dry manifold, the condenser is inserted into double tube heat exchanger configuration. The metal to metal contact between the condenser surface and heat exchanger surface provides a good heat conducting link. If a tube is to be replaced, the defective tube can simply be removed and another inserted in

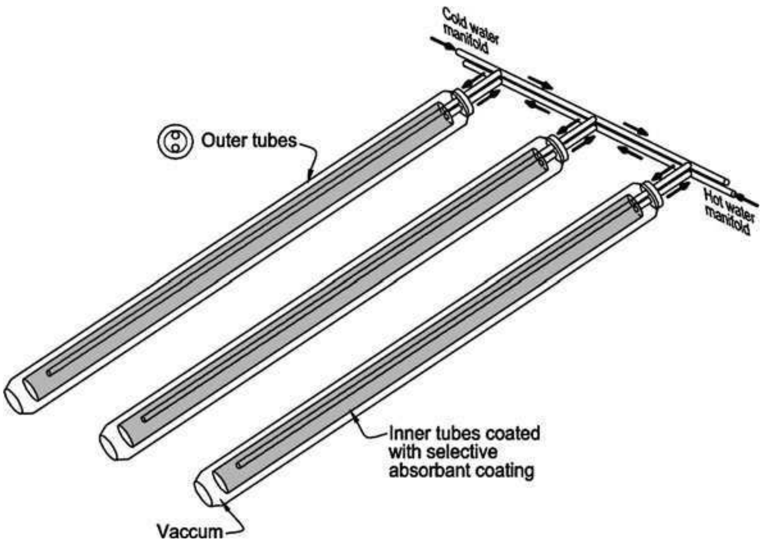


Fig. 3.63 Metal/glass water pipe evacuated tube solar collector

Fig. 3.64 Dry manifold connection for an evacuated tubular heat pipe collector array

its place without any need to drain the solar circuit. Figure 3.64 shows a dry manifold arrangement for an evacuated tubular heat pipe collector array.

Concentrating collector: To increase the insolation on the absorber surface over that incident at the collector aperture, reflectors are employed in solar water heating systems. Concentrating reflectors can obtain higher temperatures on the absorbing surface than those achievable by a flat absorber and as the absorbing surface area is reduced relative to that of the aperture, there is a reduction in the overall heat loss from the system, hence an improved thermal efficiency.

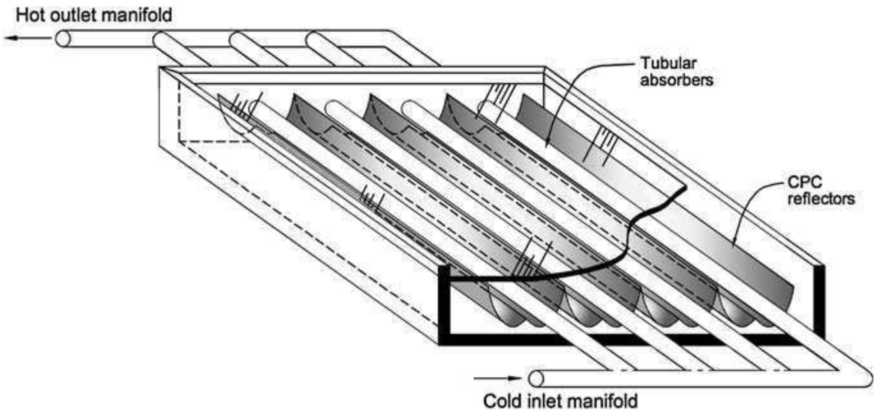


Fig. 3.65 Diagram of a compound parabolic concentrating collector

Fig. 3.66 External CPC collector with an evacuated direct flow coaxial tubular absorber

Internal reflectors are contained within the unit enclosure whereas external reflectors are located outside the sealed casing. Reflecting concentrator designs for low to medium concentrations can be flat or curved, line-axis or line-focus (circular, parabolic or compound parabolic) reflectors, symmetrical or asymmetrical. The concentrating collector used for domestic applications usually incorporate a concentrating reflector in the form of a parabolic trough or CPC (Compound Parabolic Concentrating) collector, using highly reflective surfaces to concentrate the solar radiation unto the absorber. Most absorbers are tubular, although not exclusively. Figure 3.65 illustrates a simplified external CPC collector with tubular absorber (with an upper and low manifold assembly) and Fig. 3.66 is a picture of an external CPC collector with an evacuated direct flow coaxial tubular absorber. Figure 3.67 is a close up image of an evacuated tube collector with internal concentrator and Fig. 3.68 depicts a ray trace diagram for an internal tubular absorber cusp CPC collector.

Selecting the correct collector for any application is of critical importance. It is therefore necessary to understand the characteristics of the collector and its performance, primarily through determining the collector efficiency curve. The characterisation of a solar water heating collector is based on the principle of

Fig. 3.67 An evacuated tube collector with internal concentrator

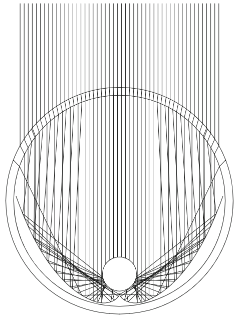


Fig. 3.68 Ray trace diagram for an internal tubular absorber cusp CPC collector with solar radiation perpendicular to the aperture of the collector

incident **sol**ar radi**ation** (insolation) being absorbed and transmitted to a working fluid. Therefore, some important parameters must be considered in order to determine the collector performance. The total amount of solar energy incident on the aperture area over a test period is given by

$$\mathrm{Q}_{\text{incident}} = I_{\text{ave}} A_{\text{ap}} \Delta \mathrm{t} \tag{3.1}$$

where

$$I_{\text{ave}} = \left(\int_{\mathrm{t}_{\text{end}}}^{\mathrm{t}_{\text{start}}} \mathrm{I}\,(\mathrm{t})\, dt \right) \Big/ \Delta \mathrm{t} \tag{3.2}$$

The useful energy gained by a collector is expressed by

$$\mathrm{Q}_{\text{col}} = \mathrm{mc_p}(T_{\text{o}} - T_{\text{i}}) \tag{3.3}$$

And thus the heat balance of the system (based on the Hottel–Whillier–Bliss equation for solar collectors that expresses the thermal performance of a collector under steady state conditions [1, 3]) is given by

$$\mathrm{mc_p}(T_{\text{o}} - T_{\text{i}}) = A_{\text{ap}} F_{\text{R}} [I_{\text{ave}}(\tau\alpha) - U_{\text{L}}(T_{\text{i}} - T_{\text{o}})] \tag{3.4}$$

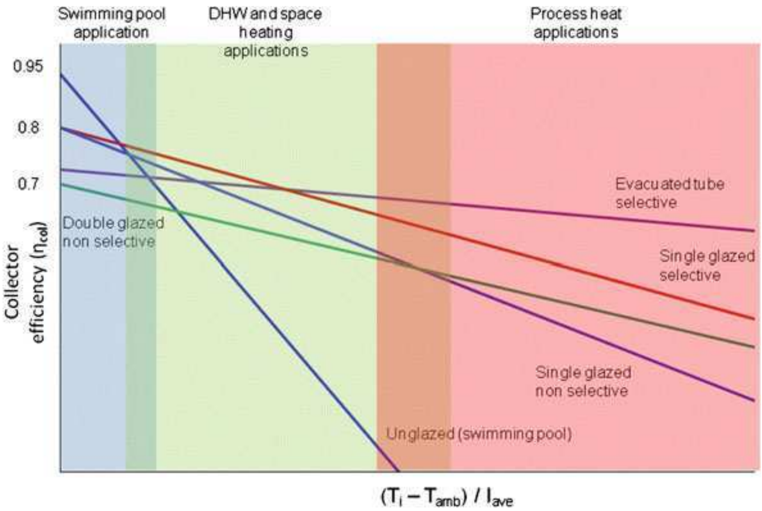


Fig. 3.69 Collector efficiency 'curves' for various collector types

Therefore the collector efficiency is defined as

$$\eta_{col} = \frac{mc_p(T_o - T_i)}{I_{ave} A_{ap}} \tag{3.5}$$

Or substituting Eq. 3.4

$$\eta_{col} = F_R(\tau\alpha) - F_R U_L \frac{(T_i - T_{amb})}{I_{ave}} \tag{3.6}$$

The above equation is a simplification of the thermal loss function of the collector following a linear heat loss rate. In some performance equations a more detailed characterisation is used

$$\eta_{col} = F_R(\tau\alpha) - a_1 T_m - a_2 I_{ave} T_m^2 \tag{3.7}$$

Where a_1 and a_2 are heat loss factors.

The performance of a solar water heating collector is often presented as a graph. The instantaneous efficiencies calculated using Eq. 3.6 are plotted against $(T_i - T_{amb}) I_{ave}$ and the intercept (F_R $(\tau\alpha)$) and the slope ($-$ F_R U_L) determined, which represent the collector optical efficiency (η_{opt}) and heat loss coefficient, respectively. Figure 3.69 illustrates the typical collector efficiency 'curves' and areas of application for various collector types.

3.5.2.4 Solar Water Heating Components

There are many components that make up any solar water heating installation, with many variations in the system configuration. Figure 3.44 details a typical schematic layout for a distributed installation using a flat plate collector indicating many of the relevant components and their location.

Heat Storage

The energy supplied by the sun does not always match the intended demand. It is therefore necessary to store the collected energy for hourly, diurnal or even seasonal use. There are a number of ways to store thermal energy and they are classified as being either sensible or latent storage:

- Sensible Energy storage (comprising rock beds, building fabric, bore holes, water stores and oil stores).
- Latent Energy Storage (Phase change materials).

In sensible energy storage systems no change of phase occurs, and thus the energy stored is given by the following simple equation.

$$Q_{store} = m\,Cp\Delta T \tag{3.8}$$

Latent energy stores can achieve higher energy densities compared with a simple sensible heat store, however significant energy is required, at constant temperature, to change a material's phase from either solid to liquid or liquid to gas. Ultimately, much more compact heat stores are possible combined with the ability to store large amounts of heat at a selected set temperature. The desirable characteristics of phase change materials are that they should have a high latent heat and permit repeated heating and cooling cycles with no degradation in performance. The phase change should occur at a given temperature with little or no superheating or supercooling. The material must have a phase change at the desired storage temperature for the intended applications and the material must be suitable for enclosure in containers that facilitate rapid heat transfer into and out of the phase change material. In general, for solar or building applications, it must be low cost with low toxicity.

Hot water tanks: For many systems the temperature of operation required is a set parameter and the materials that can be used for storage are limited. This leaves the store volume as the only parameter that can effectively be used to increase storage capacity. If significant amounts of energy are to be stored, stores can be of very large dimensions. To undertake this cost effectively for solar applications the materials used must be of low cost.

Most thermal water stores are classified according to their application (main storage or buffer), operating pressure (vented and unvented) and fabrication material. Typically, for most water heating applications the materials of choice are

Fig. 3.70 Hot water stores; (*left*) vented, copper (*twin coil*) hot water cylinder and (*right*) industrial stainless steel pressurised (unvented) buffer vessel

copper, coated steel and stainless steel. Figure 3.70 depicts a vented copper (twin coil) hot water cylinder (prior to installation) common to many small solar water heating applications and a larger unvented, pressurised stainless steel buffer vessel used in commercial and industrial applications. Both tanks incorporate an internal heat exchanger. Figure 3.71 is a commercial thermal storage tank that reverses the function of the primary (collector) and secondary (DHW supply) circuits. The primary water is stored in the cylinder and heated by the auxiliary input. Domestic hot water is supplied via an upper heat exchanger coil connected directly to the cold water feed. Like a traditional hot water store, the solar collector circuit is connected via a low level internal coil heat exchanger.

For many solar water heating systems the most common storage temperatures are between 40 and 65°C with the stores sized appropriately. Extensive work undertaken to improve storage tank performance have highlighted the advantages of stratified thermal storage in improving the solar savings fraction. Several designs have been developed to enhance this characteristic. The introduction of baffles (Fig. 3.72) at tank inlet and outlet ports also improves performance by leading to reduced disruptive flow patterns within the tank under draw-off.

Heat Exchangers

As most solar water heating systems operate in the indirect configuration, some form of heat exchanger is necessary to transfer solar collected thermal energy to the store. In the majority of small solar water heating applications, an internal coil

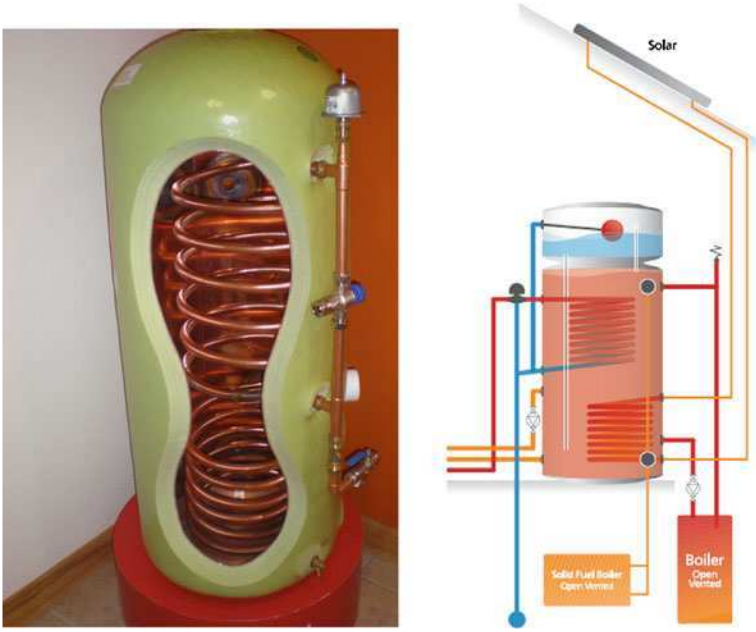


Fig. 3.71 The MaxiPod thermal storage system cut away demonstration unit and schematic diagram (reproduced by kind permission from Copper Industries Ltd)

Fig. 3.72 Baffle plate at inlet to storage tank

heat exchanger is generally sufficient. However, due to increasing system size or complexity it is common to utilise an external heat exchanger.

Internal heat exchangers are quite simply coiled runs of plain or finned pipe within the storage tank. Finned pipe coils, in comparison to plain pipes, have an increased surface area per pipe length, improving the heat transfer efficiency. There are many variations of the finned pipe; most are formed by either winding a

Fig. 3.73 Finned heater exchanger coil during the fabrication process

copper strip onto the core tube into an embedded groove or just cold rolled extruded from the core tube. Vertical installation for both forms of coil is preferred as it promotes stratification and connections to the solar circuit should be made so that the coil flow is from top to bottom. Figure 3.73 depicts a view inside a water storage tank with a finned heater exchanger coil during the fabrication process.

There are two basic types of external heat exchanger used in (solar) liquid to liquid heat transfer, albeit with a wide number of variations. These heat exchangers can be simply classified as being shell and tube or plate.

Shell and tube heat exchanger: Shell and tube heat exchangers have been around for over 150 years. The basic design is based upon a bundle of tubes in a large cylindrical shell with baffles used both to support the tubes and to direct into multiple cross flow. Gaps or clearances must be left between the baffle and the shell and between the tubes and the baffle to enable assembly. Their thermal technology and manufacturing methods are well defined and applied through modern manufacture.

Plate and frame heat exchangers: The plate and frame heat exchanger is more common in solar water heating applications. The most common variant of the plate and frame heat exchanger consists of a number of pressed, corrugated metal plates compressed together into a frame. These plates are provided with gaskets, partly to seal the spaces between adjacent plates and partly to distribute the media between the flow channels. The most common plate material is stainless steel. The heat transfer surface consists of a number of thin corrugated plates pressed out of a high grade metal. The pressed pattern on each plate surface induces turbulence and minimises stagnant areas and fouling.

Expansion Vessels

The expansion vessel is a membrane separated, enclosed metal container using a gas (air or nitrogen) as the expansion media. A flexible (glycol resistant)

Fig. 3.74 Image of a membrane expansion vessel (MEV)

membrane or diaphragm, such as EPDM, separates the gas from the solar heat transfer medium. The expansion vessel is directly connected into the solar circuit pipework (as shown in Fig. 3.44) so that it cannot be isolated and is always able to absorb the temperature related expansion and contraction of the heat transfer fluid. The expansion vessel for a solar hot water system must to be able to operate at the temperatures experienced in the solar circuit and its size is relative to the volume of HTF in the solar circuit, working pressure and temperature change that the system is subject to during its normal operation. Figure 3.74 shows a membrane expansion vessel (MEV).

Transfer Fluid

Heat transfer fluids transfer the solar collected thermal energy from the collectors to the store (heat exchanger). A suitable heat transfer fluid should be selected based upon its coefficient of expansion, viscosity, thermal capacity, freezing, boiling and flash points, corrosiveness and stability. In colder climates, the freezing point is important and the boiling point is important in situations where high temperatures may prevail. The viscosity and thermal capacity of a heat transfer fluid determine the amount of pumping energy required. A fluid with low viscosity and high specific heat capacity is easier to pump as it offers less resistance to flow and can transfer more heat.

Water and water/glycol mixtures are the most commonly used heat transfer fluids in solar water heating applications. For many solar systems the heat transfer fluid is water, used for its high thermal mass per unit volume, very low viscosity, virtually no cost, wide spread availability and non-toxic nature. Unfortunately, problems can arise with regard to pH levels or mineral content, but its biggest draw back is its relatively low boiling point and a high freezing point. This means for

many cases freeze protection is necessary, typically by using a water/glycol mixture.

Water/glycol mixtures come in various glycol-to-water ratios, depending upon the perceived freeze risk. Some mixtures may be as high as 60/40 glycol-to-water ratio. The most common 'antifreeze' fluid used in closed solar water heating systems is propylene glycol, as it is suitable for use in a single walled heat exchanger. Ethylene glycol may be used, but it is extremely toxic and should only be used in a double walled heat exchanger. Most glycols deteriorate at very high temperatures and the fluid should be replaced every three to five years, with annual checks carried out to monitor its stability and effectiveness.

Solar Pumps

Solar water heating circulators/pumps are typically of the centrifugal type as they tend to have low power consumption, low maintenance requirements and are highly reliable. The pump, controlled by a differential temperature controller, circulates the heat transfer fluid to and from the collector to the hot water store/heat exchanger (direct or indirect) and back again. This ensures that the pump is only active when the heat transfer fluid in the collectors is hotter than in the store and a useful solar gain can be achieved. Solar pumps are generally designed to operate for long periods, under high temperatures with temperature differentials of between 8 and 12 K. The pump casings are typically made from cast iron, bronze or stainless steel. Most solar pumps use an AC electrical supply, although it is not uncommon for DC pumps supplied by a PV module to be utilised.

Once the solar installation configuration has been determined, the system head (total system pressure drop) and flow requirements are used to select the appropriate pump. The pump size, for any given installation, should be able to circulate the heat transfer fluid at the design flow rate with minimum expenditure of electrical energy. A suitable pump should provide the required flow rate at the necessary head while operating at or near its optimal efficiency (Fig. 3.75).

Pipework and Fittings

To transfer collected thermal energy, all solar water heating installations require pipework to contain and circulate the operating fluid. The correct sizing and selection of materials and insulation is key to achieving a good installation.

Copper is commonly used as a pipework material for the primary solar circuit as it can withstand high temperatures and working pressures, although stainless steel is rapidly becoming popular as well. Copper piping can require a greater level of care and cost during the installation process, whilst stainless steel may cost more per unit length to purchase. Flexible stainless steel piping is also common and in many installations, cooper and stainless steel are connected together, as

Fig. 3.75 Solar pump during installation (the system controller can be seen above the pump and visual flow meter below)

shown in Fig. 3.76, although some thought should be given to preventing corrosion due to dissimilar metals in contact.

All pipework should be properly insulated and EPDM closed cell insulation is preferred in many installations. A number of commercial piping solutions exist that provide a combined flow and return pipework configuration that have been pre-insulated. Two flexible stainless steel pipes are enclosed within EPDM insulation complete with an integrated sensor cable. This pipework saves time and costs associated with the installation phase.

Any solar water heating installation requires a number of different fittings and valves. Generally, the number and type of fittings are subject to the type of pipework that has been selected and include items such as bends, T-pieces, unions/connectors and fittings for sensors. Valves are necessary to ensure the safe and effective operation of the system and permit easy maintenance and replacement of faulty components. The range of valves common to most solar water heating installations are isolation valves, regulation and/or commissioning valves, non-return valves, fill/drain valves, automatic air valves and other safety valves. Non return (or check) valves ensure that reverse circulation of hot water from the store to the collector does not occur during non-collection periods. Automatic air valves are used to remove air build up within the highest points of the system, both during

Fig. 3.76 Cooper pipework (no insulation installed) with flexible stainless steel connection to collector inlet and outlet (with insulation)

the initial fill and normal operation. Safety relief valves are necessary to stop pressure build up with the system. SRVs on the flow and return pipes of the collector can be seen in Fig. 3.76. It is common in most installations to also include a simple visual flow meter somewhere adjacent to the pump.

Controller

The main function of any solar controller is to control the solar pump so as to optimally collect solar thermal energy. These units range from a simple unit that operates based on electronic temperature difference regulation to units that also provide heat measurement, data logging and display and error diagnostics. For simple temperature difference regulation, two temperature sensors are required; one measuring the collector output, the other measuring the water store temperature at the heat exchanger connection. The pump is switched on (via a relay) when the collector is hotter than the store and switched off when the collector is cooler than the store. The switch on temperature differential is dependant on a number of factors. Generally, differentials of between 5 and 8 K are standard. Increasing the differential may lead to the fewer pump on–off cycles. The switch off differential is normally set at 3 K. Any lower may introduce the risk of stored energy being extracted from the tank, leading to a drop in system performance. Sometimes, a pump overrun time can be introduced to ensure that collected thermal energy is not left in the interconnecting solar circuit pipes when the differential falls below the switch off level. Temperature and duration settings are usually set by the solar installer, relative to the particular installation.

In some installations, a third temperature sensor may be installed to provide measurement relating to the hot water storage outlet temperature, providing the user with an indication of the hot water draw-off temperature. Safety features may

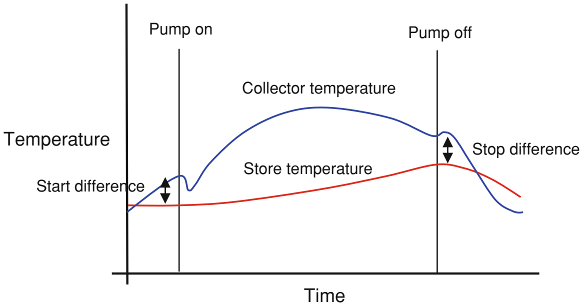


Fig. 3.77 Function of a temperature differential controller based on daily collector and storage temperature

also be a function of the controller. When the hot water storage temperature exceeds a pre-set temperature such as 65°C, hot water can be exported to another store or 'dumped'. In a drainback installation, the controller may also be used to 'drain' water from the collector by deactivating the pump, although a properly designed system should have no water in the collector and adjoining pipework, and thus have no risk of freezing (Fig. 3.77).

Most modern controllers are now required to provide much more than pump control and are commonly designed to also provide heat measurement, data logging, error diagnostics and PC interface. To be able to carry out these functions, the unit must be equipped to interface with additional sensors and output devices and carry out the necessary calculations and diagnostics.

3.5.3 Solar Thermal Power

Solar thermal power systems consist of two main parts, the solar collector system and a heat engine generally based on the Rankine cycle. (A heat engine is a device that converts heat energy into mechanical energy or more precisely a system which operates continuously where only heat and work may pass across its boundaries). However, due to the intermittent nature of solar radiation, when designing a solar thermal power system, use of extensive storage or an additional generation method is essential to enable continuous electricity production. The most common approach adopted combines solar thermal and diesel generators. A few large systems have been developed to date; all have been smaller than 100 MW electric (peak). Ambitious plans have been developed for the wide scale use of solar thermal power generation, however market forces have been insufficient to result in full implementation.

All the standard techniques to improve the heat engine efficiency used for standard power generation can and are used with solar systems. However a problem exists in that the efficiency of the heat engine will improve with increasing temperature while the efficiency of the solar collector system will decrease due to increased heat loss, thus an optimum operating temperature

Fig. 3.78 Single axis parabolic trough concentrator at the PSA solar testing facility in Almeria, Spain

Fig. 3.79 10 kW twin-axis tracking parabolic dish systems using a Stirling engine cycles at the PSA solar testing facility in Almeria, Spain

exists to obtain optimum system efficiency. It is, in general, essential to use solar concentration to generate temperatures greater than 100°C. Although the compound parabolic concentrator can achieve concentrations of two without tracking, to achieve very high temperatures greater levels of concentration are required. Single axis tracking is essential for parabolic trough based systems (Fig. 3.78) and twin axis tracking for parabolic dish systems and heliostat fields (Fig. 3.79).

To determine a system's performance, analysis of the optics and heat transfer is required. Ray trace techniques can be used for the optical analysis. Ray tracing effectively attempts to simulate the path of multiple beams of light from the

source, i.e. the sun, to the absorber, to ensure a geometry that allows as much incident radiation to fall on the absorber. Thermal analysis is either based on resistance network analogies using correlations from the literature or detailed finite element or volume analysis. Finally, at elevated temperatures radiative heat transfer suppression by using selective surface coatings is essential. Typical solar thermal power generation systems normally employ one or a combination of the following configurations.

- Flat plate solar water heaters,
- Evacuated tube, with or without concentrators,
- Parabolic trough concentrators,
- Parabolic dish concentrators,
- Heliostat field concentrators,
- Hybrid systems.

3.6 Solar Thermal Cooling

A range of solar thermal based technologies have been developed to effectively and efficiently perform a cooling/refrigeration function. Complications arise when a high temperature source of heat is desirable for good efficiency in refrigeration cycles, yet the efficiency of solar collectors decreases with increased fluid delivery temperature. Cost and availability of alternative technologies are the major factors that will determine which, (if any) and where, such systems may be used. The major technologies for solar cooling/refrigeration are:

- Absorption systems,
- Adsorption systems and
- Desiccant systems.

The range of temperature operation varies from system to system and depends on design, working fluids and power input but can cover an output range from −20 to 25°C.

3.6.1 Absorption Systems

Absorption systems can either be continuous or intermittent, the continuous systems being in general used for air conditioning and the intermittent systems used for refrigeration. A range of fluids have been employed in these systems, the most common being lithium bromide (water—LiBr) and ammonia (NH_3—water). A diagrammatic representation of an absorption system is given in Fig. 3.80.

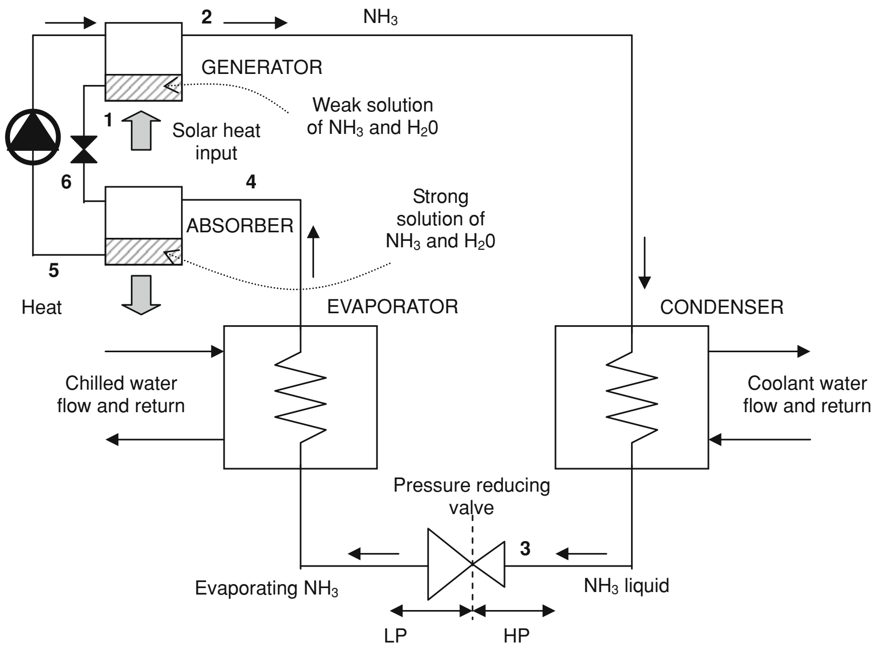


Fig. 3.80 Schematic detail of an ammonia/water (NH_3—water) absorption chilling system

From 1 to 2: Energy is supplied to the generator via solar energy. The heat separates the ammonia from the solution of water and ammonia, sometimes referred to as the 'ammoniacal solution'.

From 2 to 3: The ammonia vapour is now cooled and condensed to a liquid, giving up its enthalpy of evaporation to the condenser cooling water.

From 3 to 4: The liquid ammonia is flashed off through the pressure reducing valve to a lower pressure, which lowers its boiling point. Hence, the low-pressure liquid boils taking the heat needed from the surrounding water in the evaporator and chilling it.

From 4 to 5: Note that the pressure in the evaporator is kept low because of the high affinity that exists between the gaseous ammonia and water. The ammonia readily goes into solution, giving up its heat from the chemical reaction. In this case the chemical reaction is termed 'exothermic' (heat is given out) and this takes place in the absorber.

From 5 to 1: The circulating pump draws some of the strong ammoniacal solution from the absorber and delivers it to the generator ready for the ammonia to be boiled off.

From 1 to 6: In order to replenish the liquid in the absorber, the remaining water in the generator is allowed to flow from the relatively high pressure of the generator back to the lower pressure of the absorber via a pre-set throttling valve.

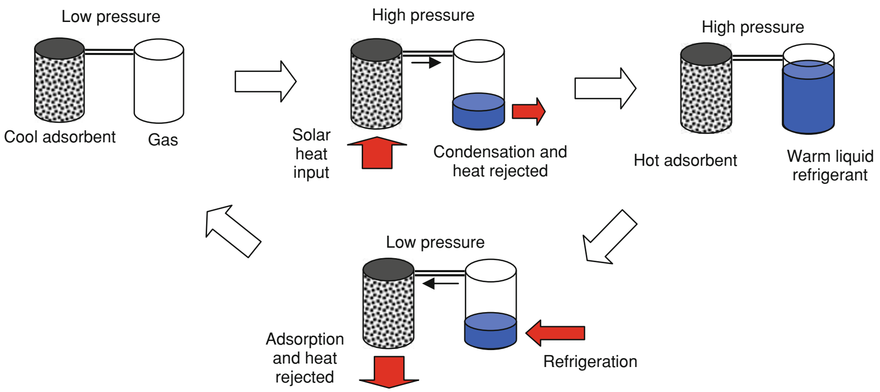


Fig. 3.81 The basic principle of adsorption cooling

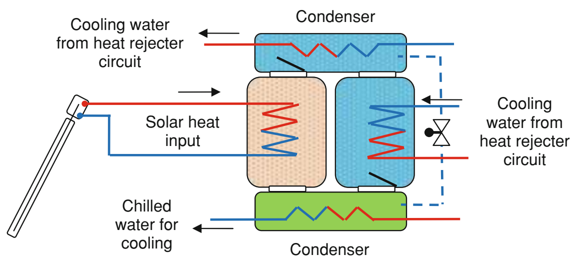


Fig. 3.82 A schematic detail of a typical adsorption system

In actual plants some of the heat of the exothermic reaction taking place in the absorber is used to supplement the energy needed in the generator, and this is done using a separate heat exchanger called an economiser.

3.6.2 Adsorption Systems

Adsorption refrigeration cycles rely on the adsorption of a refrigerant gas into an adsorbent at low pressure and subsequent desorption by heat. Current systems commonly use ammonia and carbon. They have the potential to deliver high levels of performance but require high generator temperatures (above 130°C), requiring the use of solar concentrating collectors. The basic principle is shown in Fig. 3.81.

A typical adsorption system consisting of two sorbent compartments; one evaporator and one condenser is shown in Fig. 3.82. While the sorbent in the first compartment is regenerated using heat from the solar collector, the sorbent in the compartment two (adsorber) adsorbs the water vapour entering from the evaporator. This compartment has to be cooled in order to enable a continuous

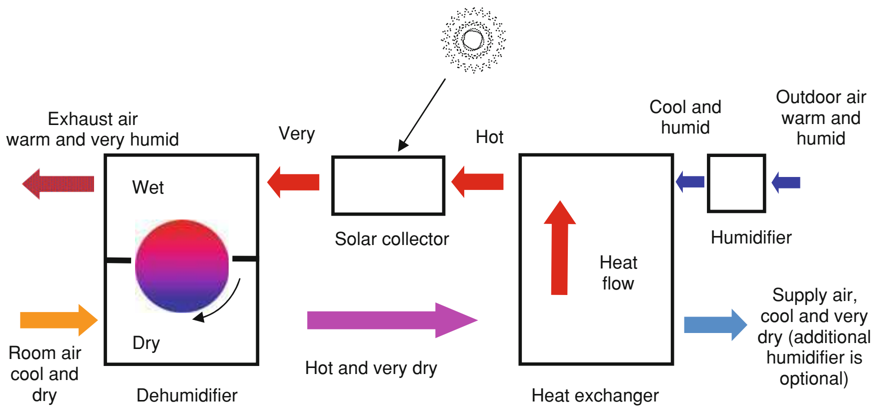


Fig. 3.83 Basic schematic detail showing the operation of a solar desiccant cooling system

adsorption. The water in the evaporator is transferred into the gas phase being heated from the external water cycle; here actually the useful cooling is produced. If the cooling capacity reduces to a certain value due to the loading of the sorbent in the adsorber, the chambers are switched over.

Current research is being undertaken to improve the system COP and the power density of the adsorbent material to 1 kW/kg by reducing the cycle time. The cycle time is governed by the time to get heat into and out of the adsorbent material and is essentially a heat transfer process.

3.6.3 Desiccant Systems

Solar supplied desiccant cooling systems take air from outside or from the building, dehumidify it with a solid or liquid desiccant, and cool it by heat exchange (with an additional option of evaporatively cooling it to the desired state). The desiccant must be regenerated by heat which is achieved with a solar energy input from either solar air collectors or solar liquid collectors. Solar air collectors can be directly integrated whilst an air/liquid heat exchanger is necessary for liquid collectors. Liquid collectors offer the additional potential of thermal storage reducing the need for auxiliary energy at non-solar collection periods. Figure 3.83 illustrates the simple operation of a solar desiccant system.

Incoming ambient air is dried and heated by a dehumidifier, after which it is cooled by extract air via the heat exchanger (regenerator) before being supplied into the space at a lower temperature. The extracted air from the space, moving in the opposite direction, is initially evaporatively cooled in the humidifier to saturation, after which it is heated by the energy removed from the heat exchanger (regenerator). Solar energy is then used to increase the temperature up to the regeneration level of the desiccant to regenerate the dehumidifier.

List of symbols

A_{ap}	Aperture area (m^2)
a_1	Thermal loss factor 1 (W/Km^2)
a_2	Thermal loss factor 2 (W/K^2m^2)
c_p	Specific heat capacity (kJ/kg°C)
I_{ave}	Insolation (W/m^2)
F_R	Collector heat removal factor
m	Mass of water (kg)
Q_{col}	Thermal energy collected (MJ)
Q_{store}	Energy stored (MJ)
T_{amb}	Average ambient temperature (K)
T_m	Mean fluid temperature as a function of the insolation (Km^2/W)
T_i	Average inlet water temperature (K)
T_o	Average outlet water temperature (K)
U_L	Collector overall heat loss coefficient (W/K)
ΔT	Temperature change from initial conditions (K)
η_{col}	Collection efficiency
η_{opt}	Optical efficiency
$\tau\alpha$	Transmission absorptive coefficient

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Chapter 4
Energy Flows in Winemaking Facilities

4.1 Energy Use in Winemaking

There are many different systems, spaces and processes required in the modern winemaking facility. Figure 4.1 schematically indicates some of the more common headings used to describe the activities associated with the production of wine. Each of these activities have a role within the modern winemaking facility and have a corresponding energy requirement, which collectively relates to an energy input necessary to produce the finished product.

To understand the process inputs and outputs that contribute to the energy use of a winemaking enterprise, one of the most effective methods is to map the supply chain so that all energy and fuel related inputs are accounted for. In simplistic terms this can be represented through vineyard and winery activities, as presented in Figs. 4.2 and 4.3, respectively.

As indicated in the previous diagrams, to accurately assess the absolute energy requirement of a commercial winemaking enterprise is quite a difficult task, due to the range and inter-relationship between variables, which includes highly variable parameters such as transportation to market or embodied energy. It is therefore more simplistic (and realistic) to determine the measurable indicators specific to each facility, namely the energy inputs that can be accounted for within the boundaries of the wine producing facility.

In a study by the South Australian Wine Industry Association and the Winemaker's Federation of Australia in partnership with the Australian Government, Department of the Environment and Heritage [1], they determined the average energy distribution by wine producing facilities in the South Australian wine industry. Figure 4.4 details their findings.

In a similar study conducted by Elmar et al. [11] on the German wine industry, the breakdown of the final energy usage in German wineries was determined. Figure 4.5 is adapted from their detailed study of 8 wineries and presents their findings.

M. Smyth et al., *Solar Energy in the Winemaking Industry*, Green Energy and Technology, DOI: 10.1007/978-0-85729-844-7_4,

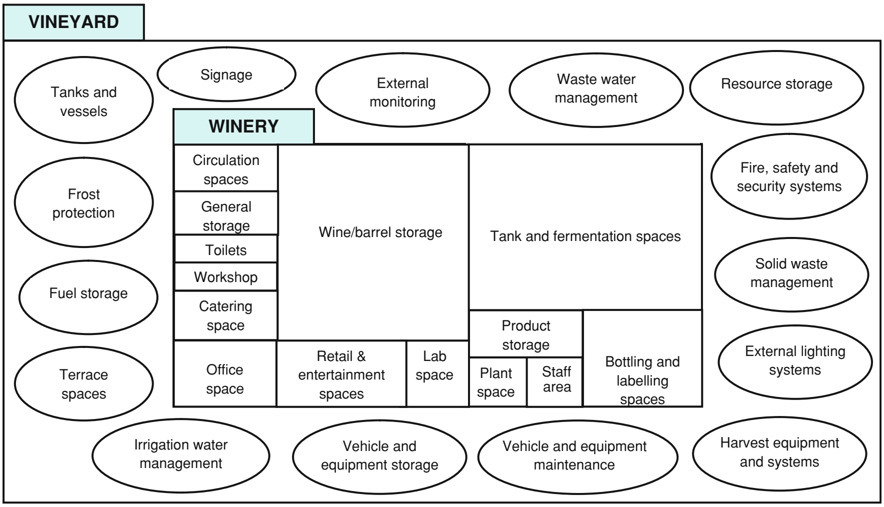


Fig. 4.1 Schematic representation of winemaking requirements

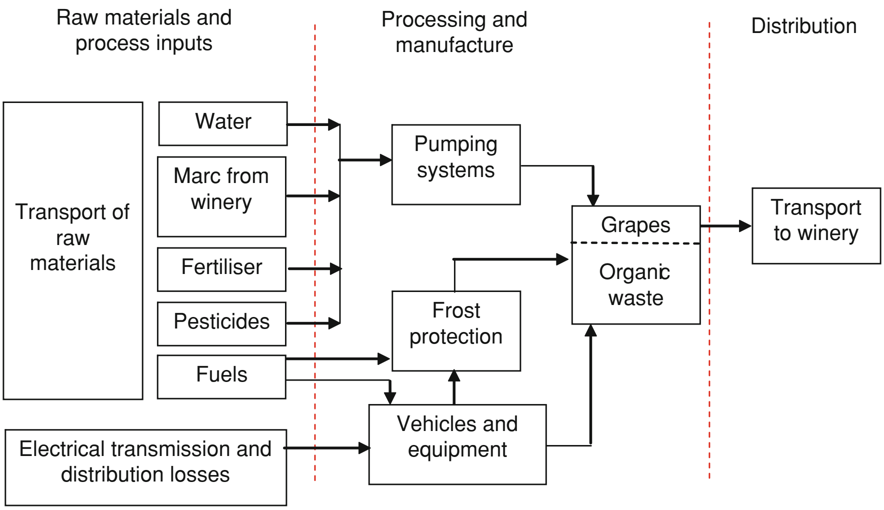


Fig. 4.2 Vineyard supply chain showing fuel and energy inputs (adapted from Forsyth et al. [14])

The distribution of energy in both these studies uses data that includes the road haulage energy usage; a value that varies greatly depending on the geographical location of the winery. This transportation factor begins with the delivery of agricultural chemical and resource requirements, barrels and bottles and follows on through to the shipment of the final product to the customer. In a study by Colman and Päster [9], entitled 'Red, White, and "Green": the Cost of Carbon in the Global Wine Trade' they calculate the carbon life cycle of wine. Whilst the

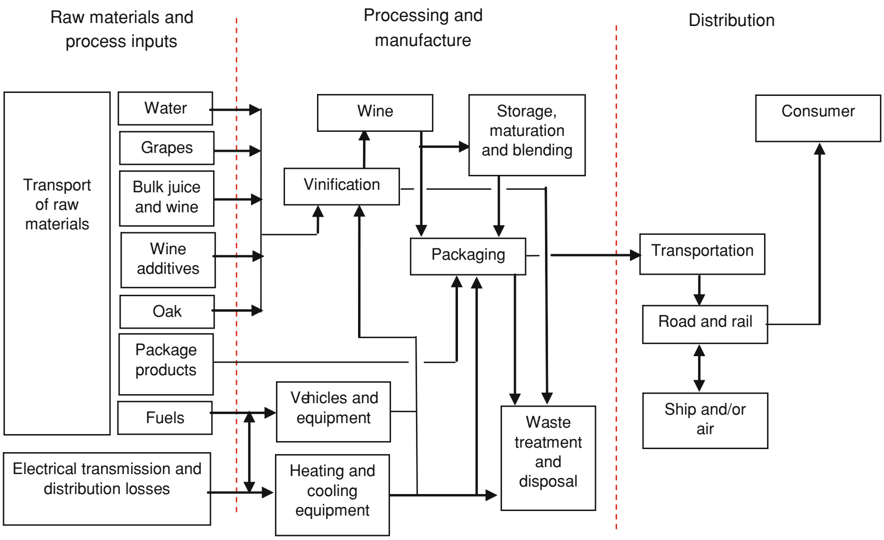


Fig. 4.3 Winery supply chain showing fuel and energy inputs (adapted from Forsyth et al. [14])

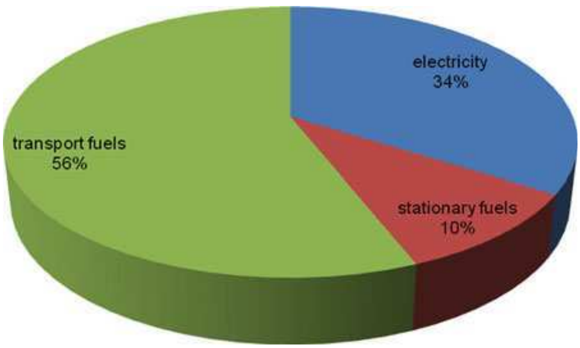


Fig. 4.4 Breakdown of total annual energy use in the South Australian wine industry [1]

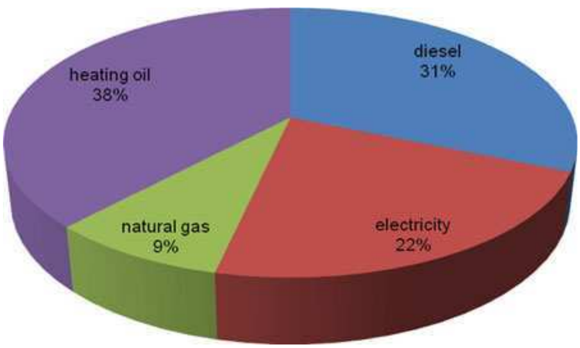


Fig. 4.5 Breakdown of total annual energy use in the German wine industry (Elmar et al. [11])

Fig. 4.6 Bulk liquid transfer and bottled gas delivery

paper does not evaluate in any detail the energy breakdown and usage in the winemaking facility, the study does show that shipping can represent a very large component (up to two-thirds in many cases) of the CO_2 output from a bottle of wine, relative to the actual production processes (Fig. 4.6).

What is interesting from the German study is the high usage of heating oil and the lower requirement of electricity. Without any specific details of the energy breakdown, it is assumed that due to the colder climate, German wineries require more heating than cooling, both in their buildings and wine production processes and thus a reduced electrical refrigeration load and increased combustion of fossil fuels for heat. Elmar et al. [11] also presented values for specific energy use per wine output based on the size of the winery for Germany, Hungary and South Africa. This data was adapted and revealed that German wineries (based on 32 wineries) used an average of 2.41 kWh/l of wine produced. South African wineries (based on eight wineries) used 2.34 kWh/l. Hungarian wineries (only 4 wineries were studied) used only 0.55 kWh/l. This dramatic reduction in energy usage by Hungarian wineries reflects the difference in the level of energy use and mechanisation in the 'modern western' winery compared to the older traditional wineries still found in Eastern Europe.

In a more recent study of the energy use within a Californian winery [28], the data is based on the energy used within the specific boundaries of the vineyard and winery facility. This study does not include haulage and shipping. Whilst it is difficult to make a direct like for like comparison, the Californian wine producer used 2.58 kWh/l of wine produced. Figure 4.7 details the annual energy breakdown.

Each winemaking facility will have varying energy profiles, but what is evident in the Californian study is the dominance of electricity. Fuel for machinery in the vineyard still represents a significant proportion at 29%, which equates to a rough estimate (for fuel consumption in a highly mechanised vineyard) of between 185 and 370 l/ha every year. Stationary fuel usage is primarily used for space, water and process heating applications within the winery, but various fuel oils and LPG are also used in stand-alone pumping applications and in areas that are particularly prone to spring frosts, significant energy (via direct and indirect combustion) are expended in frost protection measures.

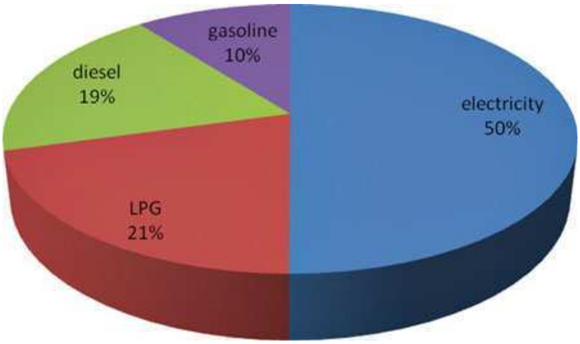


Fig. 4.7 Breakdown of total annual energy use in a Californian winemaking facility [28]

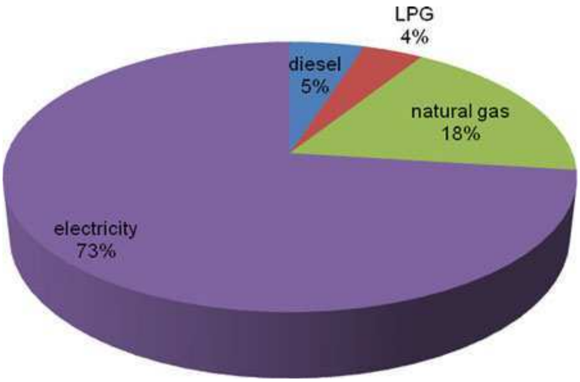


Fig. 4.8 Breakdown of total annual energy use in New Zealand wineries [30]

4.2 Energy Use in the Winery

The dominant energy segment within the winery is electricity, with gaseous and liquid fossil fuels such as natural gas, LPG and diesel making up the remainder. Typically electricity constitutes between 70 and 80%, gaseous fuels between 15 and 25% and liquid fuels less than 5%. In a study by Van der Zijpp [30], (Fig. 4.8) encompassing almost half the wine producing facilities in New Zealand, electricity was accountable for almost three quarters of the energy requirement in the wineries.

The energy distribution use in the Californian winery study [28] is shown in Fig. 4.9. Whilst slightly different in terms of fuel usage to the New Zealand study, the significance of electricity is still apparent.

In a specific study of a South Australian winery [4], the winery had a specific energy usage of 2.14 kWh/l of wine produced. Figure 4.10 details the specific breakdown in electricity and LPG.

In a study by Cotana and Cavalaglio [10] on the energy consumption of an Umbrian winery in Italy, the building covering an area of approximately 8000 m^2 used liquid, gaseous and electrical sources of energy. The winery used diesel oil and LPG boilers for steam and heat production and electricity for the majority of all the other energy requirements. The total annual winery energy consumption was 30,000 l

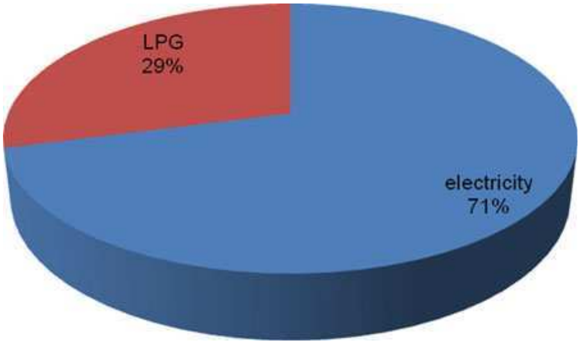


Fig. 4.9 Breakdown of the annual energy use in a Californian winery [28]

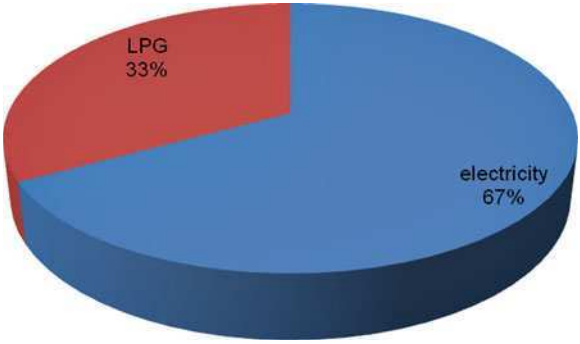


Fig. 4.10 Specific breakdown in electricity and LPG of a South Australian winery [4]

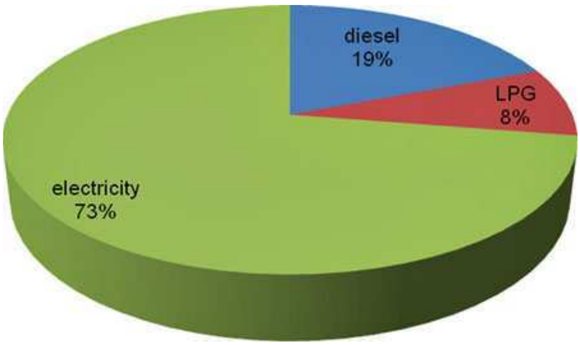


Fig. 4.11 Breakdown of the annual energy use in an Italian winery [10]

(187,500 kWh) of diesel, 11,000 l (81,400 kWh) of LPG and 709,000 kWh of electricity (with approximately 336,000 kWh used by the refrigeration equipment). These values gave an overall specific energy usage of 122 kWh/m^2. Figure 4.11 shows the annual energy distribution in the Italian winery.

Of course the distribution of energy use in the winery is not uniform over the year and can vary greatly depending on the particular activities. In a study of another Italian winery, this time in Valpolicella, Begalli et al. [6], reviewed the energy consumption of a winery during the energy intensive harvest, crush and ferment period from September to March. Figure 4.12 details the thermal and

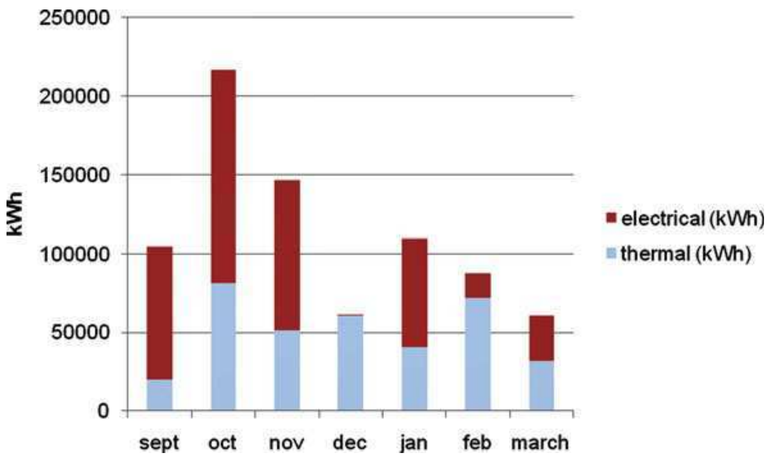


Fig. 4.12 Details the thermal and electrical requirements for a Valpolicellain winery [6]

electrical requirements for the winery at this time. No details of winery size or output were presented.

From this very simple evaluation, over this period the winery required a total of 788,051 kWhs of which just over 45% was thermal and 55% electrical.

4.2.1 Liquid Fuels Used in the Winery

As seen previously, liquid fuels, excluding road haulage values, accounts for about a third of the energy used in the winegrowing and making facility. Of this, the vast majority is used in the fuelling of vineyard equipment and to a lesser extent frost protection and stand-alone pumping installations (such as irrigation or fire protection). Figure 4.13 gives some examples of liquid fuel usage in the vineyard environment.

In Fig. 4.14 the seasonal variation in liquid fuel usage can be observed, with the bulk of the fuel being used during the growing season [28]. In addition, the difference in gasoline and diesel use is apparent. Gasoline is used in the lighter, utility vehicles which operate throughout the year while diesel is used by the heavier agricultural vehicles which have a greater level of activity in the months of March to June, in line with vineyard soil tillage and management activities.

Within the actual winery, liquid fuels such as diesel or heating oils are also used in boilers hot water production (domestic sanitation or space heating). Liquid fuels may also be used in back-up emergency power systems or large power washing units (Fig. 4.15).

Whilst there are many different liquid fuels available to the wine producer, petrol/gasoline and diesel, due to their availability are the most commonly utilised fuel by far in all winemaking establishments. However, uncertainty in supply, rising costs; high green house gas emissions are leading producers to look at alternative

Fig. 4.13 Examples of liquid fuel usage in the vineyard (clockwise from *top left*: heavy traction vehicles for grubbing; medium wheeled vehicles for vine canopy management; medium wheeled vehicles for row mowing; light wheeled vehicles for maintenance and inspection tasks; grape collection vehicles; smudge pot burners for frost protection)

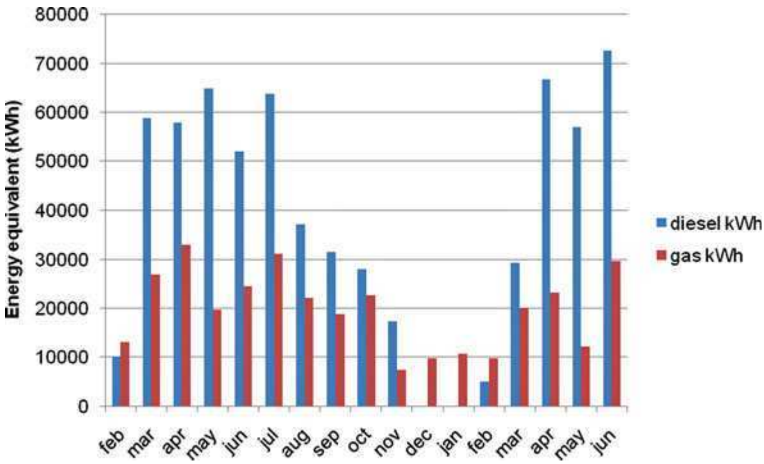


Fig. 4.14 Diesel and gasoline usage in equivalent energy (kWh) in the vineyard for a Californian winery [28]

energy fuels. Biodiesel and ethanol look very promising, although food verses fuel issues and availability may prove to be barriers to their wide-scale adoption.

4.2.2 Gaseous Fuels Used in the Winery

Gaseous fuels used in the winery environment include natural gas, Liquid Petroleum Gas (LPG) and propane. There are others, but these 3 are the most commonly

Fig. 4.15 Examples of liquid fuel usage in the winery (power washer and diesel generators)

used. Whilst some of the gaseous fuels used in the winery are attributed to transportation (fork trucks), the vast majority are used in heating processes, particularly space and water heating and cooking and food preparation. In some wineries, stand alone gas fired wind mills are used for frost protection (Fig. 4.16).

One interesting application of gas (although technically vineyard only) is that conducted by organic and sustainable farming pioneers, Long Meadow Ranch in Rutherford, California. This winery uses gaseous fuels (propane) to provide cleaner alternative vineyard heaters for frost control instead of using smudge pots and they uniquely use propane torch scorching for in-row vineyard weed control. In a more radical step, Grove Mill winery in New Zealand evaluated a prototype tractor running on a fuel gas created in a 'gasification' process using the readily available vineyard biomass. The tractor was successfully converted in 2008, proving that it is both possible and practical to power vineyard tractors through vineyard by-products. Diesel usage was reduced by 75% and CO_2 emissions by almost 0.35 ton/ha.

Current practice in wineries is to consume natural gas, where available, for large heating requirements. Due to the relative remoteness of many wineries from fixed gas pipelines, however, LPG (which is much more expensive) is often supplied by tankers. Typical consumption figures for gas fuels depend primarily on the amount of hot water or steam required for process heating; in some cases cleaning and for other requirements that occur on site. Figure 4.17 illustrates the average daily energy equivalent (kWh) for LPG usage in a Californian winery [28]. Gas fuels may also be used to power combustion engines to drive electricity generation or compressors directly (Fig. 4.18).

4.2.3 Electricity Used in the Winery

Whilst inevitably there will be significant variation in the amount of electricity used within a winery facility, it is evident in the study of both old world and new world wineries that electricity makes up the biggest energy segment by far, up to three quarters in many instances. Of this, refrigeration and chilling (40–60%) require the largest portion due to the importance of product and space temperature

Fig. 4.16 Examples of gas fuel usage in the vineyard/winery (clockwise from *top left*: wind mill frost protection; gas fired burner/boiler; gas fork truck)

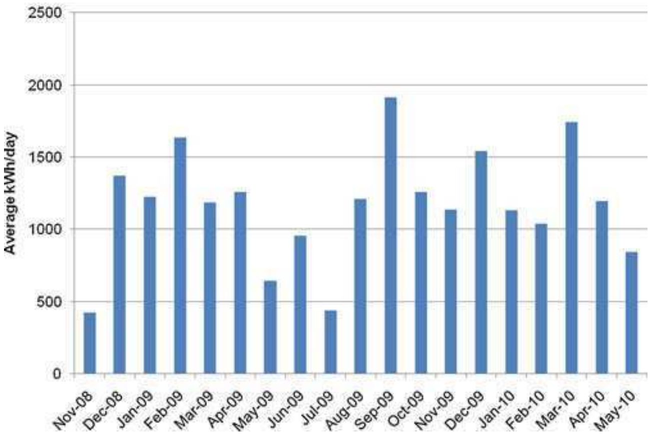


Fig. 4.17 Average daily energy equivalent (kWh) for LPG usage in a Californian winery [28]

control. Following refrigeration the other major consumption segments are rotor-dynamic equipment (10–35%), lighting (5–30%), compressed air (3–10%) and other production and building related equipment (5–30%). A more detailed evaluation is presented in the following section.

In an Australian study [2], they determined the total electrical energy used by the wine producing facilities in the Australian wine industry to be as shown in Fig. 4.19.

Fig. 4.18 LPG storage with fill station for vehicles and portable tanks

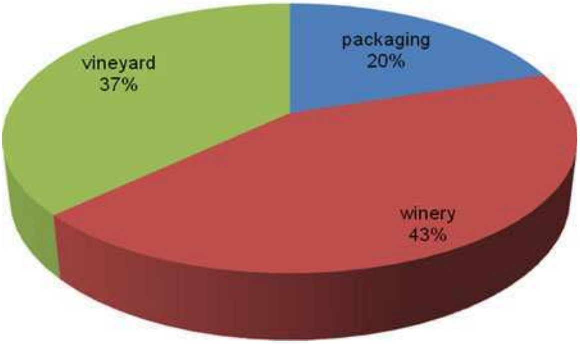


Fig. 4.19 Breakdown of total electrical energy use in the Australian wine industry [2]

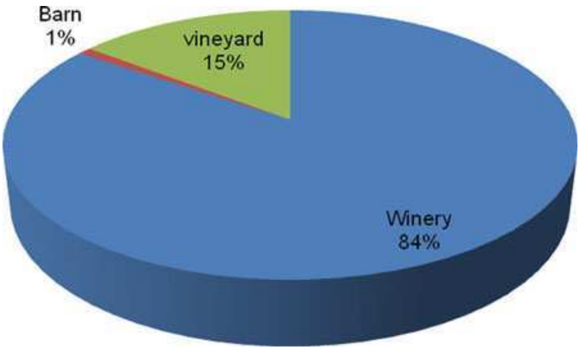


Fig. 4.20 Breakdown of total electrical energy in a Californian winery [28]

This breakdown differs significantly from the Californian study [28], shown in Fig. 4.20. Some variation may be attributed to the categorisation of energy usage, for example some of the pumping facilities that are located near to the winery have been included under the winery heading. The barn is the vineyard building from which vineyard activities can be organised and conducted.

Fig. 4.21 Electrical requirements in the vineyard (water pumping and temporary lighting during harvest)

Fig. 4.22 Battery electric powered vehicle (BEPV) [26]

Electricity use in the vineyard is primarily for the pumping of water, either for irrigation, frost protection or water transfer applications. Other vineyard electrical loads are quite small, generally related to site lighting (functional or signage) security equipment, bird scaring units or weather measurement devices (Fig. 4.21).

In a study conducted by Redpath et al. [26] the potential of Battery Electric Powered Vehicles (BEPVs) to replace conventional Internal Combustion Engine Vehicles (ICEVs) in agricultural applications was evaluated. They studied the use of a prototype battery powered electric vehicle at a monastery situated at Achkout (Lebanon) with a total agricultural area of 50 ha, of which 10 ha was under vines. The study suggests that these vehicles could augment fossil fuel-based tractors for lighter agricultural duties (Fig. 4.22).

Figure 4.23 shows one of two quad utility vehicles (Barefoot motors) used at Trefethen Family Vineyards, California. These vehicles are very adaptable and are used for general purpose tasks throughout the vineyard (approximately 8 h of charge). The image shows the quad just after a trip from the vineyard after carrying out trellis repairs (as seen by the wire and tools at the front). The winery also owns

Fig. 4.23 An electrical quad utility vehicle used at Trefethen Family Vineyards, California

and operates a 'zero motor' electric motorbike to travel around the vineyard, primarily for observational tasks.

The amount of electricity required varies over the year, although there is usually a common pattern followed by most wineries. In a study by Smyth [28], the monthly electrical profiles for a number of Californian wineries was determined and evaluated. Figures 4.24, 4.25, 4.26 and 4.27 details the profiles for some of the wineries studied.

Collectively, the annual electricity usage for a number of wineries in California was plotted against the wine production specific to that facility as shown in Fig. 4.28 [28]. Although there is a great deal of scatter, due to the diversity of the samples, the average electrical requirement per litre of wine produced for all the Californian wineries in the study equates to 0.634 kWh with an asymptotic average of around 600,000 kWhs for larger production outputs.

Based on the study of the monthly annual electricity usage, Smyth [28] determined an average profile for all of the Californian wineries evaluated in the study. Figure 4.29 shows a typical electricity demand profile for Californian wineries, based on annual percentage. It is apparent that electricity is used throughout the year. The months of September and October have the highest electrical demand, coinciding with the traditional harvest, crush and fermentation period when significant electricity is required for mechanisation and refrigeration. Two smaller peaks coincide with cold stabilisation during February and an increase in bottling activity around May.

In a study of Australian wineries [2], accounting for the difference in the hemispherical location, the profile almost mirrors the Californian profile. The major peak occurs during the harvest, crush and ferment period (March and April), with two lesser peaks occurring in September and December (Fig. 4.30).

A study by Anon [4] on a Western Australian winery also confirms this as being the typical electrical usage profile in a modern winery facility, as detailed in Fig. 4.31.

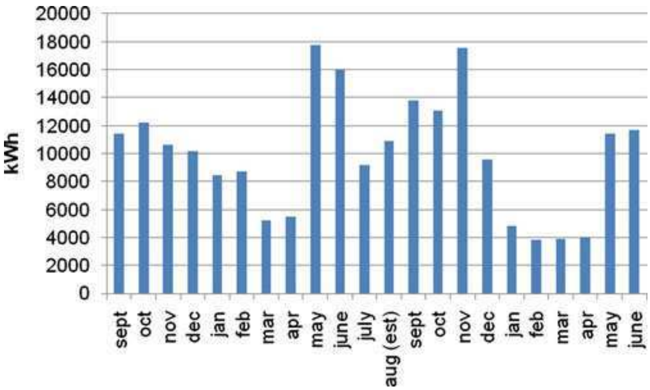


Fig. 4.24 Monthly electricity usage of small winery in Oak Knoll, Napa Valley, California using on average 126,127 kWh/year [28]

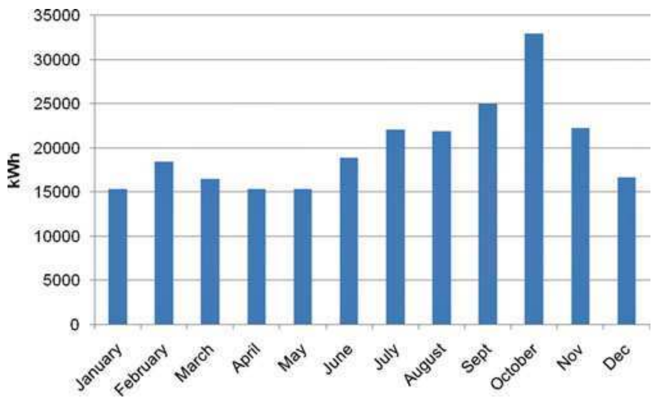
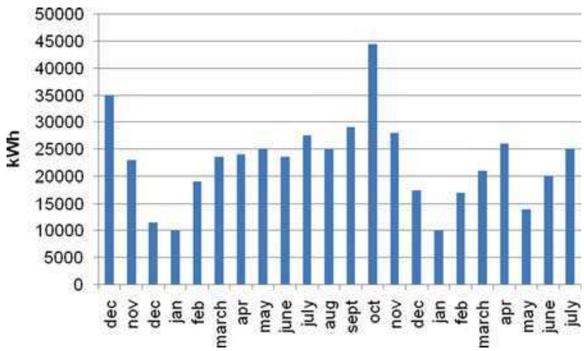


Fig. 4.25 Monthly electricity usage of small to medium sized winery in the Sonoma Valley, California using on average 240,640 kWh/year [28]

Fig. 4.26 Monthly electricity usage of medium sized winery in Rutherford, Napa Valley, California using on average 296,088 kWh/year [28]



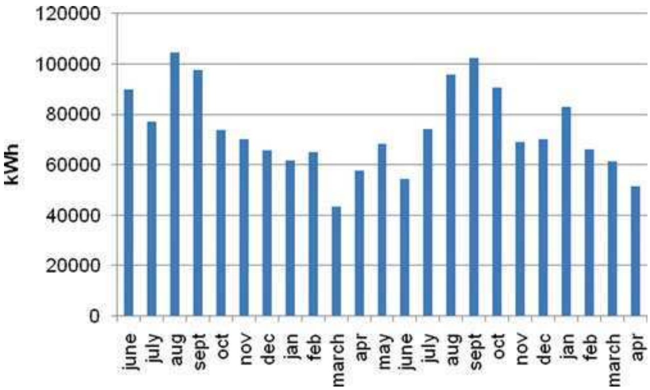


Fig. 4.27 Monthly electricity usage of medium to large sized winery in Carneros, Napa Valley, California using on average 886,497 kWh/year [28]

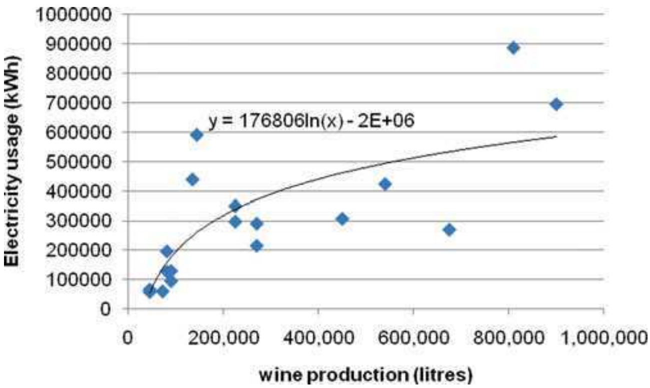


Fig. 4.28 Annual electricity usage against wine production for a number of wineries in California [28]

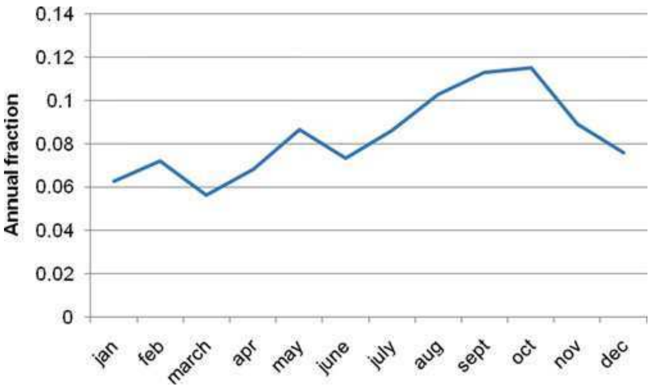


Fig. 4.29 Monthly electricity demand profile for Californian wineries [28]

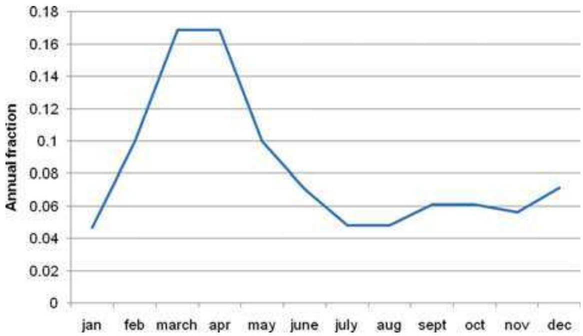


Fig. 4.30 Monthly electricity demand profile for Australian wineries (adapted from Anon [2])

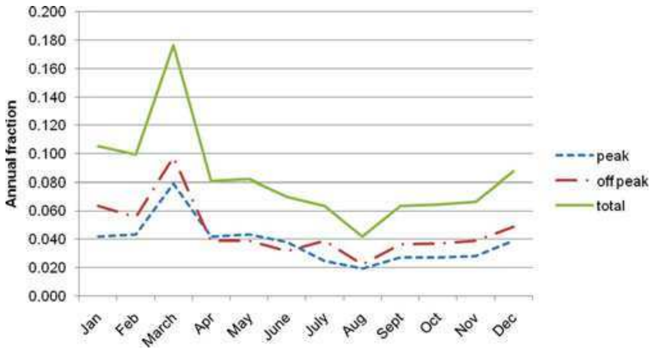


Fig. 4.31 Monthly electricity demand profile for a Western Australian winery, including peak and off peak tariff (adapted from Anon [4])

What is interesting about this study is the fact that for most of the year off peak electricity is greater than the on peak usage. This is an indication that a large percentage of the electrical requirement is needed at off peak periods, typically during the night. This is consistent with a winery operation, with cooling demand being a 24 h activity, especially for processes such as cold soaking, fermentation and cold stabilisation. In this particular winery, refrigeration represented 56% of the total electrical demand.

4.2.3.1 Electrical Loads Within the Winery

Electrical power consumption in the winemaking process can vary significantly due to winery location, wine type, size and many other factors, however, most winery electricity use can be roughly broken into the following end uses:

- Lighting
- Bottling and packaging
- Production

- Refrigeration
- Compressed air
- Pumps
- HVAC
- Other equipment
- Miscellaneous

Lighting

The need for lighting in a winery is not that different from any other production facility. The largest portion of physical luminaries and thus energy use, relates to the functional/task lighting necessary to carry out the various winemaking activities efficiently and safely within the winery spaces. External lighting for security and architectural or dramatic effect also consumes a significant portion of the annual electrical energy usage, typically 15–25% of the total lighting value [28]. Other lighting requirements can be in the form of mobile lighting equipment, specialist lighting fixtures and emergency lighting.

Typically, older facilities tend to have less efficient lighting installations with a very high relative Wattage (0.005–0.015 kW/m^2, [28]) and include such power intensive components like high intensity discharge (HID) fixtures, linear fluorescent lamps, magnetic ballasts and incandescent lamps. Such a high kW load, combined with long hours of usage ultimately leads to a high annual energy use, somewhere between 25 and 35 kWh/m^2. A benchmark winery is assumed to use 10 kWh/m^2 for lighting [19]. Lighting is usually the simplest and most cost effective energy segment to reduce in any winery and is given the highest priority during any energy refurbishment/reduction exercise. For example, switching from magnetic ballasts to electronic ballasts in HID fixtures can result in up to a 22% reduction in lighting electricity use, due to the combination of fewer luminaries, lower ballast losses and longer lamp life.

Bottling and Packaging

The energy required for bottling and packaging in a winery can vary significantly depending upon the wine style and bottling facility. Electricity is the largest energy input, but many bottling and packaging lines have significant compressed air requirements as well. The energy requirement can vary within a winery from almost zero through to 3 or 4% of the building's electrical demand. In smaller wineries where cost, production output or space makes having a dedicated bottling line impossible, the energy requirement in the bottling process is low, often a quasi-mechanical/manual process, with some electrical input for specialist equipment. In many cases the bottling process is outsourced either to a larger winery or mobile bottling facility. In larger wineries, it is more common to have an in-house bottling facility, usually in a dedicated room.

Fig. 4.32 Differing sparkling wine bottle sizes (from *left* to *right*)—Salmanazar (9 l), Jeroboam (3 l), Magnum (1.5 l), Standard (0.75 l) and Half (0.375 l)

Fig. 4.33 Australian wine cartons

Generally speaking, sparkling wine lines are much more energy intensive compared to still wine bottling lines, as the bottling line for each wine style differs significantly. Both bottling lines have a number of common items of equipment, such as accumulator platforms and conveyors, bottle filler, bottle washing and sterilisation, corker, labeller, quality control, box sealing and control systems that can be modified to suit a wide range of bottle types. However, sparkling lines also have a tirage line, disgorger equipment (bottle neck freezing equipment, disgorger and doser), wire hooder and dosage blender, all of which require more energy, especially the disgorging equipment. Still wine bottling and packaging has been monitored at 0.002 kWh/l [28] and 0.0028 kWh/l [19]. Bottling and packaging energy usage by a sparkling wine producer was measured at 0.065 kWh/l [28] and the total bottling and packaging energy usage by a still/sparkling wine producer was between 0.032 and 0.042 kWh/l. A more detailed study of the bottling and packaging activities is presented in Sects. 4.3.1 and 4.3.2.

Fig. 4.34 Wine pouch and filling machine

Of course, not all bottles are a standard 0.75 l. Bottles come in a range of shapes and sizes, all of which require a different bottling set up, although the basic process is the same and the energy inputs may not vary significantly (under an automated process). Figure 4.32 illustrates the range of bottle sizes that can complicate an automated process. Generally, for sparkling production, up to 1.5 l can be accommodated with the automated bottling line, larger requires a manual input. The ‘bag in the box’ packaging arrangement does differ, however. This form of packaging is preferred by some wineries because it is less expensive, lighter and more environmentally friendly than the bottled format. It does, however, require a different filling process. Figure 4.33 depicts an Australian wine carton and Fig. 4.34 shows a wine pouch and filling machine (supplied by Astrapouch North America).

Once the wine is bottled and packaged, the energy input is not finished. The various packaging materials and boxed wine needs to be transferred between storage spaces. Whilst this can be manual, in the larger wineries these transferring activities are exclusively done by electric fork trucks. In a typical situation, a fork truck can be kept continually active from leaving empty bottles at one end of the bottling line to removing the boxed, palletised finished product at the other (see “Miscellaneous” for more details). Figure 4.35 depicts fork truck and manual pallet truck operation in the bottling and packaging line and Fig. 4.36 shows a fully automated palletisation and wrapping unit at the end of a bottling line.

Production

Wine production is the ‘rasion d’etre’ for any winery. Whilst the wine production activities within a winery can be specifically itemised, it could be argued that almost all activities carried out within the winery could be contributing to the wine production process. However, keeping to specifics, this section will only look at the activities that are unique to the winemaking process, from grape arrival at the winery to entering the bottling line. There are many items of plant that are exclusive to wine production and they include the following:

Fig. 4.35 Manual palletisation and wrapping at the end of a bottling line

Fig. 4.36 Automated palletisation and wrapping at the end of a bottling line

- Grape arrival and immediate processing: grape hopper, sorting table and de-stemming unit
- Grape pressing units
- Fermentation—thermal and mechanical processing: fermentation tanks, mobile pumping units, mobile glycol chilling and heating units, mixing systems
- Separation and Filtration: centrifuge separator, pad/membrane filter, cross-flow filter, reverse osmosis unit
- Washing and sterilisation: ozone sterilisation unit, SO_2 portable injector, in-line steam injectors, barrel washer
- Riddling units
- Quality control: measurement and monitoring systems, laboratory testing and analysis equipment

Grape Arrival and Immediate Processing

On arrival from the vineyard, speed is essential in processing the grapes to ensure quality. Depending on the wine style the sequence of immediate processing can

Fig. 4.37 Large weigh station on entrance to winery (Sonoma Wine Company)

differ, but in all cases the grapes arrive at a central distribution point. Many mechanisms in receiving the grapes from the harvest bins have evolved to suit the various winery layouts. In still wine, typically the grapes are dumped into a hopper from which an elevator (belt or Archimedes screw) delivers (typically 2–10 ton/h) the grapes to a sorting table. Wineries can and often will process between 10 and 100 ton/h, by skipping the sorting table and loading directly to the crusher (de-stemmer). In sparkling wine, the grapes are delivered directly to the press. Most equipment does not require a large load, usually powered by a single phase 2–3 HP motor. They will however, be operating continuously throughout the harvest collection period (Figs. 4.37, 4.38, 4.39).

The grapes (along with unwanted debris) travel along the sorting table to the de-stemmer. Typically, in the modern winery, vibrating sorting tables (Fig. 4.40) or sorters that use blowers (Fig. 4.41) are popular. The grapes travel on the vibrating table as clusters where shot berries and other debris fall through the slotted surface, a jet of air can then be used to further remove other lighter, non-grape material.

Equipment exists that de-stems only, or de-stems and crushes or crushes first and then de-stems. The older (obsolete) method of mechanical de-stemming consists of having the crushing rollers located before the de-stemmer. However, crushing stems can release phenolic compounds into the must, therefore de-stemming before crushing is the most common arrangement in quality wine production. In almost all equipment the space between the crushing rollers can be adjusted and some equipment allows the rollers to be removed if crushing is not desired for the wine style. Rubber rollers are available with some equipment. The crushing rollers should be designed and spaced to allow for crushing without chopping or flattening the skins, cracking the seeds or breaking an excessive amount of stem tissue. Like the conveyor equipment, the loads are not excessive, but again are in operation throughout the harvest collection period (Figs. 4.42 and 4.43).

After sorting, crushing and de-stemming, the grape/must is transferred to the press (typically as in white wine) or tank (as in red wine). Fork trucks (or pumps) transfer the grape/must to the next reception point (Fig. 4.44).

Fig. 4.38 Mechanical elevator equipment; hopper via conveyor to press (*left*), auger transfer (*centre*) and hopper to combined elevator and sorting table (*right*)

Fig. 4.39 Large scale production with a multi-hopper grape reception area

Grape Pressing Units

Sooner or later (white or red), the grapes must be pressed. Many mechanical devices have evolved over the years to carry out this process, from physical manual presses to highly automated, computer controlled units. Of course quality is everything and the quality of the pressed wine or juice and the production method or wine style selected is determined by the various press actions.

In most modern wineries some powered pressing device is used, batch or continuous. Previously, a vertical basket press was the most common press in operation. It consisted of a large basket that is filled with the crushed grapes. Pressure is applied through a plate that is forced down using a screw or hydraulic device. The juice flows through openings in the basket. A modification and improvement on this design was the moving head press. Today, however, in most medium to large wineries, pneumatic batch presses are preferred. These can be either bladder or membrane. In the bladder design compressed air inflates an internal bag made of thick rubber that runs the axis of the press cylinder. The bag presses the must against an outer perforated, cylindrical stainless steel cage that acts as a sieve. To break up the press cake the pressure on the bladder is released and the horizontal cage is rotated. The cake falls down and is taken by an auger to

Fig. 4.40 Vibrating sorting table and de-stemming

Fig. 4.41 Sorting table with blower and several sorting stages

collection where it can be removed from the press area. In smaller wineries a water operated bladder press may be used. This press is built like the traditional vertical basket press but has an internal rubber bladder that is inflated to produce the pressing action. Mains water pressure may be adequate to inflate the bladder and press the grapes evenly against the basket. In the membrane design, the same principle of pneumatic pressure is utilised, but the physical action differs. In the membrane system, the membrane is the same shape and size as one half of the press and is mounted at the diameter of the cylindrical press. When the membrane is sucked back against one surface of the press, the void allows the entire volume of the press to be filled with grapes. The membrane can then be inflated to press the grapes against the drain screens in the opposite hemisphere of the press. As these types of presses are batch, many wineries will use two presses, so one unit will be pressing whilst the other is being emptied and refilled.

Whist most presses are primarily utilising pressurised air or water, significant electrical energy is necessary to power various rotodynamic devices

Fig. 4.42 View inside the de-stemmer with location of external power supply and control equipment

Fig. 4.43 Small de-stemming and crushing unit

Fig. 4.44 Chardonnay grapes being transferred and dumped into the press

Fig. 4.45 Small membrane presses

Fig. 4.46 Medium press, with detail of bladder and auger to remove marc

Fig. 4.47 Large membrane press equipment located outdoors

(pumps, compressors, actuation devices, augers) and control equipment. The electrical requirement of the press varies significantly with the press output requirement, small mobile, single phase 1.5 kW units to large stationary, three phase 35 kW units (Figs. 4.45, 4.46, 4.47).

The previously mentioned presses are all batch type production. A continuous screw press offers a continuous press output (impulse and belt systems also exist).

Fig. 4.48 Evaporator for juice concentration

An Archimedes screw continuously forces grapes up against the solid wall, extracting the juice and allowing the pomace to continue through to the end where it is collected. This style of press does not produce quality wines.

After pressing, the resulting juice is a mixture that is high in suspended solids and other particulates. At this stage, the juice will often undergo clarification, to reduce the level of solids prior to the fermentation. Juice clarification (particularly white) can be carried out in several different ways:

- Natural settling: static clarification of the juice will naturally occur over time, providing there is no fermentation. Reducing the juice temperature, applying enzyme treatments or the use of filtration aids (bentonite and/or gelatine) can all be used to assist natural separation
- Filtration: with or without filtration aids
- Centrifugation: an effective mechanical mechanism of removing solids from juice
- Flotation: fine gas bubbles are introduced into a constantly moving juice and due to surface tension, the suspended solids attach to the bubbles and float to the surface where they are collected.

The continual flotation process offers the quickest and most energy efficient means of juice clarification, although cooling and mechanical power is still necessary. The ideal flotation temperature is around 15°C and clarifying agents (bentonite, gelatine, etc.) are usually added to improve agglomerate creation. Typical portable flotation units are rated from 3 m^3/h requiring 3 kW to 10 m^3/h requiring 8.5 kW.

In some situations, when some harvested/pressed juice has lower sugar levels than desired, an evaporator may be used to concentrate the juice by extracting water under low pressure/heated conditions. Figure 4.48 depicts an evaporator

Fig. 4.49 Open top red wine (vat) tank with complete wall heat exchanger

used in a US winery. There are many variations of systems in operation; vacuum evaporative pan, falling film and climbing film in both tubular and plate formats. This technology is more common in European wineries, and is more widely used in other fruit juice production processes. Reverse osmosis may also be utilised. This is detailed in a later section.

Fermentation: Thermal and Mechanical Processing

There are many thermodynamic and rotodynamic interactions in the modern winery. If we concentrate on wine production, the actions of thermal control and transferring/mixing the juice/wine between various vinification stages, the main power consuming equipment revolve around the fermentation tank (fermentor) and its subsequent chilling and heating, pumping connections and mixing systems. Technically speaking, a passive fermentation tank (and barrel fermentation for that matter) requires very little direct power, perhaps a 5 W supply to a control unit, for example. These tanks, however, must be suitably designed to accommodate the energy using features. Active fermentation tanks directly integrate all the thermal and mechanical activities and in these tanks a significant electrical connection is necessary.

The fermentor design really comes down to wine style; short-and-wide (1:3 to 3:1) for red (Fig. 4.49), tall-and-skinny (1:3 to 1:8) for white (Fig. 4.50) or barrels for certain reds and other oak fermented whites. In red wines the tendency is to maximise the top surface area whilst in white wines the goal is to minimize the top surface area and maximise the potential cooling wall surface area. In red wines cap management is important, of which there are many different methods; punch-down, pump-over, rack-and-return, submerged cap and rotary fermentation are common. It is for this action that open top vats, bins and tanks are the preferred

Fig. 4.50 White wine tanks with complete wall heat exchanger

type of fermentors as access through the entire fermentation cap is easier than through an access hatch of a closed general-purpose tank.

In the modern winery, there may be a range of different fermentor types in use. Sealed versions are dominant in white wine and sparkling production but in many wineries due to a range of wine styles being produced, the general-purpose wine storage tank is common. As the name implies, general-purpose tanks are the most flexible fermentors and can be adapted for most cap management regimes. A version of these general-purpose tanks with duel functionality is known as FFL tanks (fitted for lids), they can be used in the fermentation of red wine (without a sealed lid), and fermentation of white wine when fitted with a solid lid and gasket (Fig. 4.51). Most tanks are made from stainless steel although plastic, wood, mild steel, concrete and fibreglass can be used, coming in a range of shapes and sizes (Figs. 4.52, 4.53, 4.54).

In small stainless steel tanks with volumes less than 5,700 l (1500 US gallons), temperature control, whilst desirable, is less critical, as the surface-area-to-volume ratio of the tank is such that most of the heat generated by fermentation will radiate away before the temperature gets high enough to endanger the yeast cells. In larger tanks, some sort of cooling system is needed. In addition, fermentation tends to be highly stratified and therefore the cooling (heat exchange surfaces) must be designed accordingly. The cooling (and heating) exchange surfaces are of the upmost importance, as a poorly conceived tank design can have a dramatic effect upon the energy used (and wine quality) in the fermentation process within.

The location of the winery (or position of the tanks) will also dictate the fermentor design. Many wineries will have fermentors located outside which may be insulated. Space constrictions may apply and thus fermentors can also be made to custom requirements. Figures 4.55, 4.56, 4.57 and 4.58 depict a range of sealed SS tank forms in use, both inside and outside, with and without insulation.

Fig. 4.51 FFL tanks (*left*) which can be fitted with canvas top (*centre*) for red wine production and a solid lid (*right*) for white wine production

Fig. 4.52 Modern concrete fermenter (*left*), oak fermenters (*centre*) and SS tank with no integrated heat exchanger (*right*)

Fig. 4.53 Entrance to pre-cast concrete container (*left*) and fibre glass tanks (*right*)

To insulate or not to insulate is a big issue in the operation of fermentation tanks. And there are many views on what is best. In many wineries, un-insulated fermentors are located outdoors, perhaps with no coverage in direct exposure to solar radiation and local ambient air temperatures. At the other end of the spectrum, some wineries have opted to fully enclose and insulate their fermentors. In Fig. 4.58, the image on the far right is of a winery that had external, insulated tanks, but during refurbishment of the facility they built an enclosure around the tanks. In the majority of winemaking facilities, the fermentors are enclosed within a ferment room, but left un-insulated. The entire space is cooled to a lower ambient

Fig. 4.54 External tanks with a capacity of 5,00,000 l each

temperature and thus heat gain to the tanks is minimal. This approach also allows for the aesthetic benefits of the tanks to be in full view for any visitors.

In a study of the Sonoma Wine Company (SWC), a custom crush service provider in Sonoma County, California, Rosenblum [27] details the electricity used in tank refrigeration and compares the usage against a baseline case provided by the California Sustainable Winegrowers Alliance (CSWA). The study determined that 930,000 kWh was used in wine cooling for the 47 tanks (0.069 kWh/l) which was significantly higher than the suggested 675,000 kWh (0.05 kWh/l) by the CSWA. Condensation on the tank surface leads to ice build up. This change of state absorbs significant energy, leading to an increase in the refrigeration load. This was calculated in the SWC to be equivalent to 145,000 kWh (0.107 kWh/l), whilst a baseline value of 105,000 kWh (0.0078 kWh/l) was presented. Good building design, coupled with tank insulation using an external vapour barrier to reduce external tank condensation was able to reduce the electricity used in refrigeration from 1,860,000–840,000 kWh, even though production went up from 1.5 to 3 million cases.

Whether closed or open, squat or thin, cylindrical or cuboid, flat based or conical, inside or outside, the vast majority of modern wine producers utilise passive 304 or 316 stainless steel, sanitary grade tanks (mirror finish on inside and marble finish on the outside). The tanks with an integrated heat exchange jacket are capable of withstanding pressures of 240 kPa under typical flow rates of 10 to 20 l/min [20]. The tanks are fitted with a sample tap and either Tri-Clamp Butterfly valves, wine thread, BSM or Garolla fittings to which temporary piping/pumping arrangements are connected (as well as external through-valve mixers). Closed tanks have factory installed vents. Tanks may have level gauges and wall access can be via either oval or rectangular tank doors.

Figure 4.59 indicates some of the various ancillary tank equipment fixtures and instrumentation necessary on a modern winery fermentor, and Fig. 4.60 shows a fixed glycol cooling system with isolating and flow control valves.

Fig. 4.55 Sealed (uninsulated) fermentation tanks inside and outside

Fig. 4.56 Fermentors located in cellars and caves

Fig. 4.57 Cuboid tanks above ground

Not all wineries will have a fixed cooling (or heating) glycol loop installed (see "Refrigeration"), and in these instances, portable chilling/heating units or fixed ethylene glycol brine/direct expansion heat exchangers can be used where the wine is pumped to the heat exchangers and returned to the tank. From an energy point of view, it is important to get the correct size of chilling unit, which will ultimately be based on a number of factors; volume of wine, temperature differential, ambient

Fig. 4.58 Different fermentor arrangements (*left* to *right*—covered and un-insulated, exposed and insulated, inside and insulated)

Fig. 4.59 Various ancillary tank equipment fixtures and instrumentation (*left* to *right*—access door and control panel; sample fill tap; air-trap)

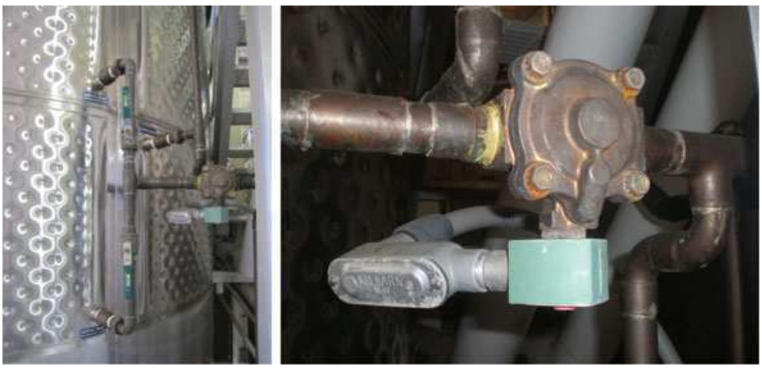


Fig. 4.60 Fixed glycol cooling connection complete with isolating and flow control valves

Fig. 4.61 A portable glycol heating system connected into a fixed glycol chilling installation (single and multiple tanks)

conditions, tank design and insulation, tank location, cooling time, etc. Pregler [24] presents a simple mechanism to size any portable chiller, and once a required refrigeration rate is achieved, one refrigerant ton (RT) being equal to 4.72 horsepower which is equal to 3.5 kW, a suitable chiller can be selected. Figure 4.61 depicts a portable glycol heating system connected into a fixed glycol chilling installation. The inclusion of individual connection points at each fermentor permits direct integration on a tank by tank basis. Whilst not comparable in the energy usage related to the chilling requirements of a winery, there are times when heat may be required such as starting a ferment, maintenance of malolactic fermentation or activities in a colder environment when the wine may be too cold to process. The size of the heating unit required is again a function of the heating load and the local ambient and tank conditions.

In addition, as previously mentioned, the fermentors will allow for some form of mechanical agitation and mixing, for activities such as cap management or wine de-stratification. Portable mixing units are very common, and most fermentors are designed to accommodate their insertion. Figure 4.62 depicts a mixer and the same unit connected to a sealed cuboid fermentor. Figure 4.63 shows a fermentor with a top integral mixing unit with internal mixing paddles. Note that this fermentor is portable and fork truck compatible.

The fermentors (for primarily red wine production) must also incorporate or allow for cap management. During a red wine fermentation, a cap of skins floats to the surface of the must and they must be re-suspended to maximize colour and flavour extraction and stop the cap from drying out. Figure 4.64 shows a low-tech method using a compressed air activated paddle which physically ‘punchs’ down the cap (see Sect. 4.3.2). In this example an open vat fermentor is used and no complicated integration is necessary. Rotary fermentors with permanent or portable rotary vanes are also used in which the entire tank is periodically mixed. Figure 4.65 details a new pump over system being developed at UC Davis,

Fig. 4.62 Portable mixing units

Fig. 4.63 Integrated mixing unit on a fork truck compatible portable fermentor (*inset*: internal view of the mixing paddles)

California. This system pumps wine from the bottom of the tank over the top of the cap in a carefully controlled manner.

Separation and Filtration

In the winemaking process, clarification and stabilisation of the wine involves removing insoluble and suspended materials from the wine. In nearly all modern

Fig. 4.64 Cap management using compressed air mechanical punching

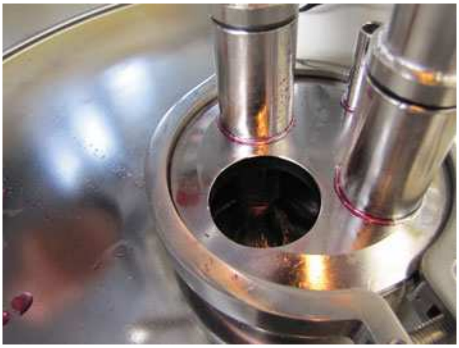


Fig. 4.65 View from above looking into the cap management pump over technique being developed at UC Davis, California

wineries this requires some form filtration or centrifugation, which requires a power input. There are other processes, but these are discussed in Sects. 4.3.1 and 4.3.2. The exact timing of the separation/filtration process and what type is to be used will depend upon the desired finish of the wine by the winemaker.

The common forms of filtration in a winery can be classified as being either depth filtration or surface filtration, although centrifugation, where wine is put through a centrifuge decanter and gravity separates the particles from the wine, is also common. In any winemaking process several levels of filtration are necessary. Depth filtration requires the wine to be pushed through a thick layer of pads (sheet filtration or plate and frame filtration) made from cellulose fibres, diatomaceous earth (DE) or perlite which traps the particles and permits the wine to pass through. Another form of depth filtration that is growing in popularity in the wine industry

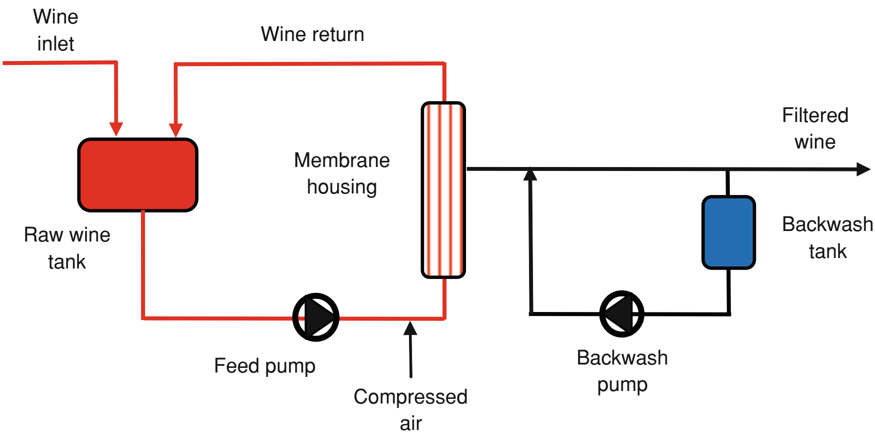


Fig. 4.66 Simple diagram of a cross flow filtration unit

Fig. 4.67 Cross flow filtration

is lenticular, modular or stacked disc filtrations. Surface filtration involves running the wine parallel to a thin film of polymer/ceramic material filled with holes smaller than the particles that are being filtered out. This type of filtration is known as cross flow and reduces the amount of potential clogging of the filter. A fourth form of filtration exists; reverse osmosis (RO), a surface filtration method typically used for sugar concentration or alcohol removal.

Cross Flow Unit

The equipment of a cross flow filter unit is relatively simple in operation and construction. Primarily consisting of a circulation pump, stainless steel fittings and valves to direct the wine flow, filter housings for the membranes and control systems (Figs. 4.66 and 4.67). A single filter housing has a flow through of up to 1100 l/h. Increasing the number of housings will increase flow through, for

example 30 housings can filter in excess of 23000 l/h. Of course an increase in housings means an increased pump size, and thus energy input, although VSDs can reduce consumption. A single housing, cross filter unit is rated at 25 kW, delivering approximately 1000 l/h (Fig. 4.67).

Depth Filtration

There are two types of depth filtration commonly used in the modern winery; plate and frame (pad) and lenticular. Depth filtration is all about stacking multiple filter layers of pads or discs, thus concentrating the level of filtration into a small footprint. The level of filtration is based on the type of filtration required by the winemaker. A sterilizing filtration with pads may allow a flow of 75 l/h across each pad, whilst a polishing filtration may increase the flow to 130 l/h. Plate and frame filters are available in 20, 40, 60, 80 or 100 plate settings. Between each plate are the individual filter pads (400, 1600 or 3600 cm^2), thus a 40 plate and frame filter holding 39 pads and using $40\times$ 40 cm (1600 cm^2) will give 6.24 m^2. The lenticular filter is based on a circular housing or canister that is secured to a base plate with a clamp closure. The housings are designed to accommodate stacks of filter discs (300 mm or 400 mm in diameter). As in the plate and frame filter, the number of discs and stack packages can be selected to give a required total filter surface area. The difference between the two types of depth filter is how they contain the filter medium and ultimately the set-up, breakdown and cleaning times. The lenticular filter is significantly easier to set-up and clean and whilst using more expensive filter media, it is less complex to operate and has a decreased likelihood of contamination/oxidation of the wine (Figs. 4.68, 4.69).

Eventually, the filter medium (pads or discs) will plug with retentate and will need to be changed. As the filter medium collects the particles, the pressure (and thus pumping) will increase. At an inlet value of 1.5 bar, the filtration is finished and the system can be taken apart and the filters cleaned. Power consumption by this type of filter is minimal as the system is passive, utilising the pressure developed by the mobile pumping unit. In comparison with the cross flow filter, cost is the defining issue. Depth filtration requires less capital input and has a significantly lower operating energy cost.

In addition to above, there are two other forms of depth filtration that, whilst not as common as pad filtration, are still used in the winemaking process; pressure leaf filtration and cartridge filtration. Pressure leaf filters are available in two formats; vertical and horizontal. Diatomaceous earth (or perlite), as the filtration medium, is added to the juice/wine/lees and the combined liquid pumped into the pressure filter vessel. Initially, the filtration medium builds up as a cake layer on a metal screen. Once a suitable layer has built up, pressure is developed, restricting the impurities. Clear juice/wine flows from the leaves (filter elements) into the tubular collection manifold to be discharged from the bottom of the leaf. As the leaves start to block due to wet cake formation, the supply pump is stopped and steam or compressed air is applied from the top (without reducing the vessel pressure) to remove the cake build up. The cake and unfiltered juice/wine is retained in the vessel and the process

Fig. 4.68 Pad filter with section panels

Fig. 4.69 Pad filtration with diatomaceous earth

repeated. Pressure leaf filters are typically in the range from 5 to 30 kW. Due to their high capital cost, high operator training requirement and health concerns, pressure leaf filters are not without their critics in the wine industry. However, they are a very cost effective form of filtration, giving very good filtration results, and with perlite filter mediums, they can be much safer to operate.

Cartridge (membrane) filters utilise a thin, flexible plastic membrane or SS 316 sheet containing a large number of very small holes. They are typically used for a sterile filtration to be carried out just prior to bottling. Cartridge filters can also be arranged to offer a single pass through two grades of cartridges. Cartridge filters are relatively expensive and are limited in their ability to deal with 'dirty' wines.

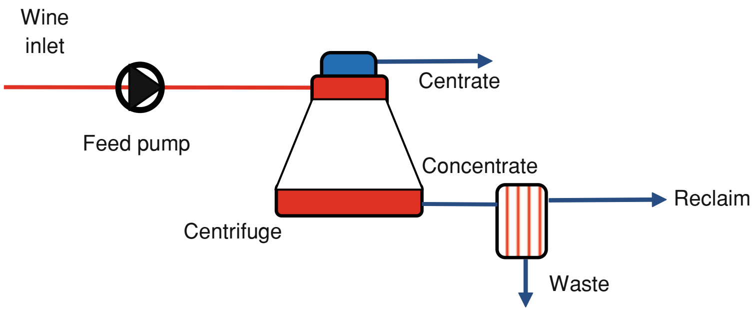


Fig. 4.70 Simplified diagram of centrifuge separation

Another form of depth filter that can be used in winemaking applications, but due to its cost, is only applicable in very large installations is the Rotary Drum Vacuum (RDV) filter. The RDV filter is a continuous filter whereby a porous stainless steel filter cloth coated with perlite powder (wound around a drum) is partially submerged and rotated through a tank of must. A vacuum is applied to the inner surface, drawing the juice through the porous filter cloth. The solids accumulate on the surface as a cake or layer and are scraped off by a blade through the rotating action of the drum. RDV filters range from small 3.5 kW units to large 50 kW units.

Centrifuge Separator

The centrifuge separator consists essentially of a compartment spun about a central axis which separates the contained materials. The unit separates the liquid element from the solids (or liquid/liquid) through their specific weight differential by means of the centrifugal motion. The higher the differential, the easier the separation. The feed wine is pumped to the centrifugal separator and the centrate (wine) is taken from the separator outlet. The unwanted particles are drawn of at the bottom in the concentrate, although some wine may be reclaimed from this waste. There are two types of centrifuge separator commonly used in the modern winery; disc bowl and decanter. The decanter is more applicable at the early stages of the winemaking process in removing larger solids, whilst the disc bowl is more often used towards the end of the process (Figs. 4.70, 4.71).

Reverse Osmosis (Alcohol Removal)

Alcohol removal remains a relatively infrequent process in the wine industry. Removing alcohol from wine or any other alcoholic product these days either involves distillation or reverse osmosis. From a quality point of view, distillation does not result in quality wine, and therefore in many situations, reverse osmosis is preferred. As the removal of alcohol from a wine is very rare, most wineries would not have dedicated equipment. In most instances, it is to partially de-alcoholise the wine to reduce the alcohol content. In these situations a temporary reverse osmosis

Fig. 4.71 Centrifuge separator

unit is hired for this unique requirement. In overall terms this would not represent a significant energy load for the winery (Figs. 4.72, 4.73).

Reverse osmosis, although still not common in many wineries, can be used in a number of other winemaking roles. Based on the ability to pass smaller molecules through the semi-permeable membrane more readily than larger molecules, RO can be used to reduce volatile acidity, remove taint compounds and remove water from grape musts, increasing sugar concentration.

Washing and Sterilisation

Wine production equipment and process line hygiene is very important, requiring a significant amount cleaning and sterilisation of pipes and fittings, tanks and equipment. Whilst the largest energy input to the sanitation process is in the form of hot water, there are many other items of powered equipment that are also common in the winery. Water heating for production or process sanitation is not to be confused with water heating of domestic water for the building sanitary appliances. In both cases, most hot water production is derived from combustion of liquid or gaseous fuels via a central boiler installation. Section 4.4.1 details this process in greater detail.

SO_2 Injection

SO_2 is used in many winemaking activities, but this section deals with its use as a disinfectant. SO_2 is a very effective poison and is used in cleaning and disinfecting barrels and other winery equipment. In most situations, the SO_2 is mixed with hot water and thus portable SO_2 injectors are used. From a power requirement point of view, these items of equipment do use significant levels of energy (Fig. 4.74).

Ozone Equipment

Many wineries have started using ozone for barrel cleaning and sanitation, tank cleaning and sanitation, clean-in-place (CIP) systems and general surface

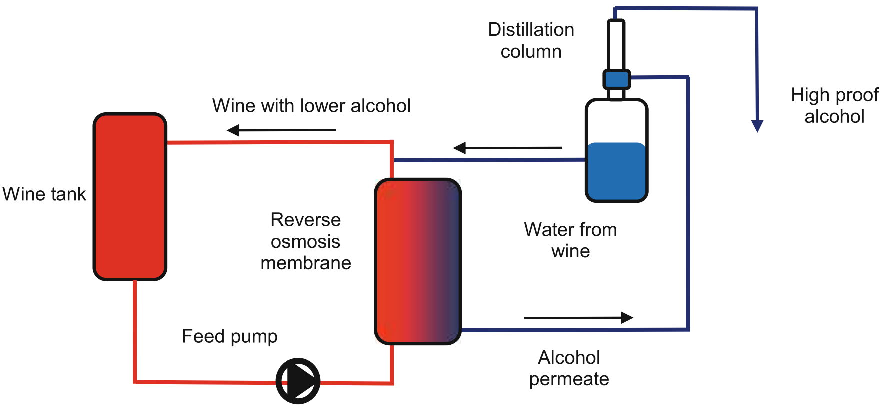


Fig. 4.72 Simplified diagram of reverse osmosis filtration

Fig. 4.73 Reverse osmosis filtration

sanitation. In the wine industry, ozone systems tend to be mobile, although they can be fixed where one load may predominate. Ozone is generated by irradiation of an air stream with ultra-violet (UV) light at a wavelength of 185 nm or by passing dry air or oxygen through a corona discharge (CD technology) generator. For low ozone concentrations (0.14% by weight), UV equipment is sufficient. For more demanding situations, where higher ozone concentrations (1.0–14% by weight) are required, CD systems are used. The energy usage of a ozone delivery system is dependent on how much ozone at a certain flow rate is required. For CIP, 75 l/min may be desired, necessitating a larger system, while only 37.5 l/min at a lower concentration may provide satisfactory barrel washing. For comparison, a typical mobile ozone generator, capable of supplying 22.7 l/min of sanitation water, with up to 5% ozone concentration by weight, requires a single phase supply of around 2 kW. Larger CD systems may require a larger electrical supply as they may be water-cooled opposed to air-cooled (Fig. 4.75).

Fig. 4.74 SO_2 injector

Fig. 4.75 Portable ozone unit

Steam Injection

Steam generation and injector units are used quite extensively in the wine industry, especially by the bigger producers. Steam, whilst more expensive to produce per

Fig. 4.76 Mobile steam generating units

litre, allows sterilisation with minimal use of water, no chemicals and reduced wastewater treatment, leading to significant operational savings. The steam generators can be stationary centralised units with dedicated fixed piping to outlet stations, but mobile, wheeled units give much more flexibility. Steam generators typically require an electrical three phase supply for the 10 kW units and up, although smaller single phase units are available, but their steam production is much lower. Common sizes found in the winery are 10, 15, 20, 25 and 30 kW systems. Figure 4.76 depicts two variations in steam generators.

Hose washing or pressure washers can use in excess of 200 l of water per hour, whilst a small steam unit can use as little as 2 l/h. Of course operating temperatures are much higher, up to 200°C as opposed to 80°C from a traditional centralised boiler or pressure washer. However, steam at 200°C at atmospheric pressure is superheated and this dry steam, with perhaps 5% relative humidity, can transfer heat very rapidly reducing the time needed to clean and sterilize equipment. Steam is not applicable for all cleaning activities in the winery and is typically used in the bottling line, barrel cleaning and hydration and tank sanitation.

Steam Cleaning Bottling Lines

The use of steam in the bottling line assures a complete kill rate in the whole system from the membrane filter to the fill spouts. The fact that the bottling line reaches disinfecting temperatures faster and reaches a higher temperature means the process is much shorter, saving a great deal of time in the sterilization process. The process only takes 15 min at over 100°C. The effectiveness in sterilizing a bottling line with steam allows 100% permeation, touching all the hard to reach nooks and crannies in the bottling line and spouts. In bottling line sterilization, the rule of thumb 1 kW per spout, so to sterilize a 16-spout mono-block requires a minimum rating of 16 kW [25]. A 20 kW unit with low pressure settings is usually sufficient for steaming mono-blocks (depending on spout count) and barrels. A 20 kW steam unit will use six gallons per hour (22.7 l/h) opposed to three to seven gallons of water per minute (11.35–26.5 l/min) for a standard hot water unit. Excluding losses and efficiency factors, 1135 l (300 US gallons per hour (5×60))

of water heated from 20 to 80°C requires 284.8 MJ. Producing steam from 20°C through to 200°C for 22.7 l/h (6 gallons per hour) through sensible and latent heat transfer requires 63.61 MJ (7.59 MJ + 51.3 MJ + 4.72 MJ).

Steam Cleaning Wine Barrels

The elevated temperature of steam allows for a much faster cleaning process of the barrels. Steam effectively penetrates the cracks and joints of the barrel and the cellulous structure of the wood, allowing for a deep clean. The steam allows for the removal of tartrates and old wine and bitter tannins that have been absorbed by the wood. Some winemakers, however, question the use of steam in expensive European oak barrels, thinking it could possibly volatilize flavours. Steam has also benefits for barrel re-hydration and checking the integrity of the barrels (steam will penetrate and reveal any leaks). A small 20 kW steam generator is suitable, although a low pressure setting is necessary as the barrel can be ruptured. It is worth mentioning, however, that some barrel washing can also be effectively done through ultrasonic methods.

Cleaning Tanks

Cleaning stainless steel tanks is one time where higher pressure and kW rating are an advantage, primarily due to the volume of the vessels. Typically, a steam unit can completely sterilize a 7,500 l tank in 15 min (at a pressure of 550 kPa) with no-one having to enter the tank. Simply connect the steam generator to an inlet valve and open the lowest valve for drainage, with an open valve/access to prevent excessive pressure build-up.

Dedicated Barrel Washing Unit

Barrel washing is necessary to maintain barrel hygiene and to remove tartrate build up to ensure that the wood is exposed to the wine. Barrel washing systems come in a variety of designs, ranging from individual barrel washing by hand to automated 'production' style barrel washing units. Note that for all systems, the hot water generators are separate units. The washer systems can be classified [23] as follows:

Leg Washer

Sometimes referred to as the "peg leg", this is the simplest system, consisting of a four-leg assembly that stands inside the barrel and supports the wash head. Designed to be used with a barrel resting on a Western Square type rack, the washer head is inserted into the downward facing bunghole to permit drainage. The winery worker manually turns the barrel, inserts the wash head and physically turns on the system.

Vacuum System

This washer incorporates a vacuum system to remove (reclaim) the wash water at the same time that the spray head is washing the barrel. In this system, the barrel

Fig. 4.77 Dedicated semi-automatic barrel washer

Fig. 4.78 Fully automated barrel filling, emptying and washing equipment

bunghole is facing up, thereby reducing labour and speeding up the process. With this type of cleaning it is very important that the flow rates of water, both into and out off the barrel are identical otherwise pooling of water can result, reducing the cleaning effect of the spray in that area. Vacuum systems can typically clean 20–30 barrels per hour.

Hand-Truck Washers

The barrel is positioned onto a horizontal rack with rollers and rotated so that the spray head can be inserted into the bunghole at the side of the barrel. The rack is rotated backwards like a hand-truck, inverting the barrel with the bunghole facing down. The design is counterbalanced to ease this movement. Less expensive units require this be done manually whilst more expensive designs will have a motor to rotate the barrel and can also come with timing systems to set wash cycles.

Semi-Automatic and Fully Automatic Washers

These systems are used primarily by big wineries processing large numbers of barrels and needing a fast turnaround. A semi-automatic, two-barrel or four-barrel washer requires a fork truck operator to place a rack of barrels onto a stationary unit. The barrels will be elevated off the rack via rollers, and the cellar worker will position the barrels such that two/four wash heads can be inserted automatically. A cycle will begin with the heads entering the barrels, followed by any combination of pre-programmed hot or cold wash, possibly followed by ozonated water. Figure 4.77 shows the operation of a typical unit.

Fully automated systems are custom-fabricated for each individual facility (Fig. 4.78). These systems also require a fork truck to deliver the barrel rack. Thereafter the racks move on a series of tracks to independent stations that incorporate any number of cycles, from emptying the wine, washing, ozonating and refilling the barrels. This is accomplished by using sensors for positioning and timers to move the barrels through the process. The only manual operation might be to remove and insert bungs.

In barrel washing, water temperature, flow rate and pressure are important considerations. For tartrate removal, temperatures ranging from 60 to 80°C are necessary. Barrel washing at this temperature, however, is sanitation rather than sterilisation. Washer manufacturers suggest a flow rate that varies as much as 11–30 l/min, with a recommended wash cycle of 2–4 min. Pressures can range from 400 to 10000 kPa depending upon the equipment. Flow rate and time can have a substantial impact on water and energy usage.

Riddling Units

Riddling is something that is very specific to the production of sparkling wines and is the act of mechanically rotating the bottles. In smaller producers, the energy demand would be low to non-existent. In larger, modern wineries, riddling, whilst high in kW load, due to the periodic motion of the riddler unit, the annual electrical energy use is actually quite low. Section 4.3.1 presents more detail on this process.

Quality Control

Quality control is crucial to the modern winery. For each stage in the winemaking process, many variables need to be monitored and measured, analysis made and appropriate actions formulated. The main stages of analysis can be grouped as pre-harvest, harvest, fermentation, post-fermentation, maturation, fining and bottle preparation. In addition to the thermo-dynamic variables such as temperature, flow rate, pressure, etc. that need to be monitored in the working winery spaces, many instruments are needed in the laboratory. Jacobson [16] suggests (in addition to regular tasting), that items of laboratory equipment are necessary to measure and analysis Brix levels (and thus sugar levels and dryness), L-malic Acid (LMA) levels, Residual Reducing Sugars (RRS) via enzymatic analysis, Titratable Acidity

(TA) and pH levels, Alcohol levels, Sulphur Dioxide (SO_2) levels and Volatile Acidity (VA). In addition, winery laboratories will also need a range of ancillary equipment to prepare, calibrate, wash and sterilise samples and equipment.

Most of the equipment used in measurement and monitoring, testing and analysis is generally low power. Individually this does not utilise significant levels of power. However, the duration and collective operation of many devices can represent a significant energy usage over a year. For example, an alcolyzer rated at 30 Watts on continuously can use 262 kWh/year. Or 20 fermentation tanks each with a 5 W temperature monitoring unit on can use 870 kWh/year.

A more detailed study of the production activities are presented in Sects. 4.3.1 and 4.3.2.

Refrigeration

Refrigeration can be the biggest single energy requirement in a winery. Refrigeration in a winery is typically grouped according to demand as either HVAC (Heating, Ventilation and Air Conditioning) or production chilling. In most wineries, the building HVAC and production demands are met through separate refrigeration installations although in some cases, storage space cooling is provided by the dedicated production refrigeration equipment. Traditional building HVAC and refrigeration is dealt with in a following section.

The principle requirement for production refrigeration (chilling) in a winery can be categorised as:

- Heat removal from the juice during harvest
- Temperature control during fermentation
- Cold stabilisation
- Climate control of wine storage spaces

And (in sparkling wine producers)

- Bottle neck freezing in disgorgement

Of course, not to be ignored is the need for heat in some wine production processes. In these instances, refrigeration equipment, or more correctly, heat pumps can be used. However, in most wineries the need is small and separate electric heating or combustion based equipment is preferred.

The most widely used refrigerators used in winemaking facilities (and heat pumps) are those which use a liquefiable vapour as the refrigerant. The evaporation and condensation processes take place when the fluid is receiving and rejecting the specific enthalpy of vaporisation, and these processes are constant temperature and constant pressure. The concept is that of a reversed heat engine and the cycle is that of the reversed Carnot cycle for a vapour. However, due to practical considerations, the ideal cycle is modified to create the vapour compression cycle. The other type of refrigeration system that, if not common, is also used in wineries is the ‘sorption’ system. Within this sub-heading, there are

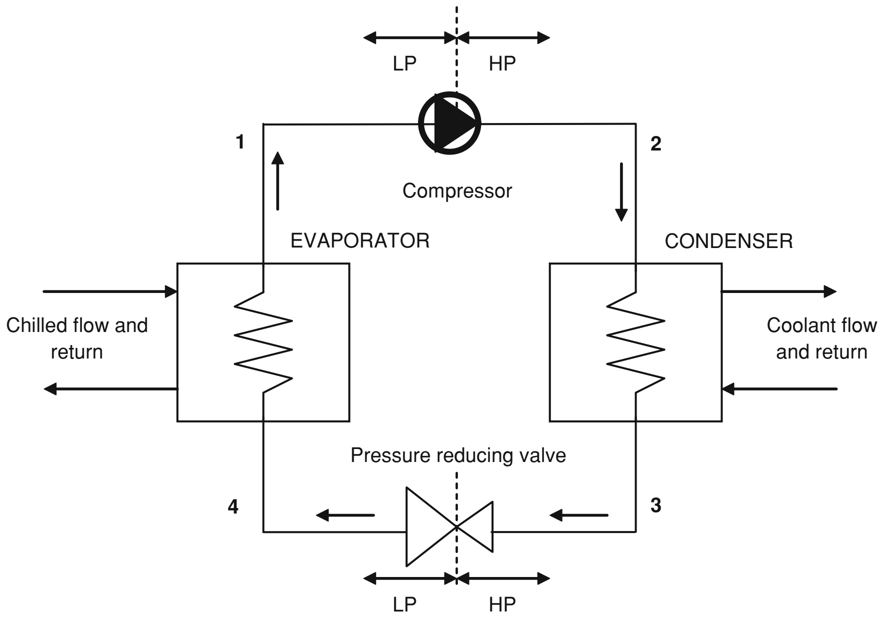


Fig. 4.79 Schematic diagram of the vapour compression components and operation

two main types of ‘sorption’ refrigeration technologies; absorption and adsorption. ‘Sorption’ systems are thermally driven systems, in which the conventional mechanical compressor (as in a vapour compression cycle) is replaced by a ‘thermal compressor’ and a sorbent. The sorbent can be either solid in the case of adsorption systems or liquid for absorption systems. When the sorbent is heated, it desorbs the refrigerant vapour at the condenser pressure. The vapour is then liquefied in the condenser, flows through an expansion valve and enters the evaporator. When the sorbent is cooled, it reabsorbs vapour and thus maintains low pressure in the evaporator. The liquefied refrigerant in the evaporator absorbs heat from the refrigerated fluid and vaporises, producing the cooling effect. Absorption and vapour compression systems can provide a continuous cooling capacity, whilst adsorption systems are cyclical in operation and thus require multiple adsorbent beds to provide an approximately continuous capacity.

Both forms of refrigeration (vapour compression and ‘sorption’) have their particular merits. However, the detailed study of these technologies is not within the scope of this chapter. Sorption systems lend themselves very nicely to solar integration and thus have been discussed in greater detail in Sect. 3.6.2. Vapour compression technologies remain the most common form of refrigeration in winery operation and thus some basic outline of their operation is presented. Figure 4.79 schematically illustrates the components and operation of the vapour compression cycle.

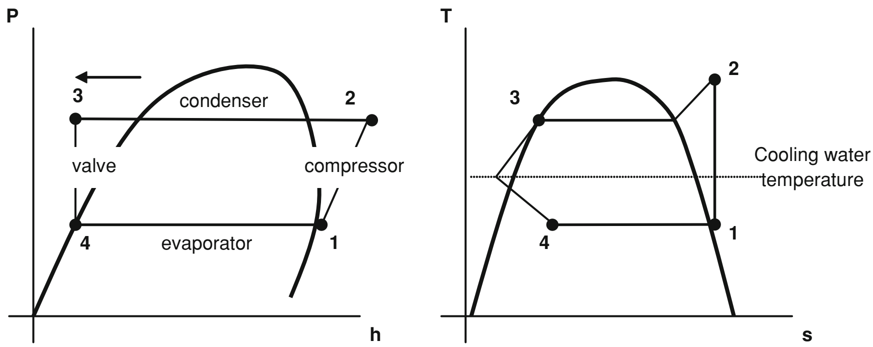


Fig. 4.80 P–h and T–s diagrams for the vapour compression components and operation

From 1 to 2

The superheated vapour enters the compressor where its pressure is raised. There will also be a big increase in the temperature, because a proportion of the energy put into the compression process is transferred to the refrigerant.

From 2 to 3

The high pressure superheated gas passes from the compressor into the condenser. The initial part of the cooling process de-superheats the gas before it is then turned back into liquid. The cooling for this process is usually achieved by using air or water. A further reduction in temperature happens in the pipework and liquid receiver, so that the refrigerant liquid is sub-cooled as it enters the expansion device.

From 3 to 4

The high pressure sub-cooled liquid passes through the expansion device, which reduces its pressure and controls the flow into the evaporator.

From 4 to 1

Low pressure liquid refrigerant in the evaporator absorbs heat from its surroundings. During this process it changes its state from a liquid to a gas, and at the evaporator exit it is slightly superheated.

This cycle is thermodynamically represented in the P–h and T–s diagrams in Fig. 4.80.

The efficiency of a refrigeration cycle is given as the energy supplied divided by the energy input. In most cases the efficiency of refrigerators or heat pumps is given in terms of the Coefficient of Performance (COP). The processes involved can be seen in the various P–h and T–s diagrams, and the COP's derived from them.

Compressor work done $= h_2 - h_1$
Refrigerating effect $= h_1 - h_4$
Heating effect $= h_2 - h_3$

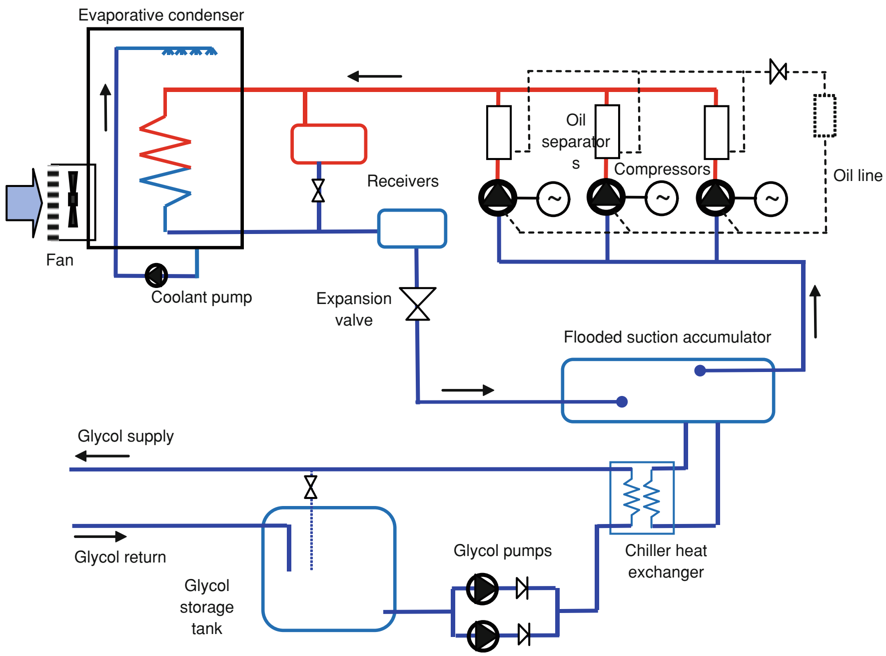


Fig. 4.81 Schematic detail a typical chiller plant set up for a winery

therefore

$$COP_{HP} = \frac{h_2 - h_3}{h_2 - h_1} \quad COP_{REF} = \frac{h_1 - h_4}{h_2 - h_1} \tag{4.1}$$

so $COP_{HP} = COP_{REF} + 1$

In nearly all large refrigeration systems, the chilling plant consists of two loops; the refrigerant loop (as detailed previously) and a second closed coolant (typically glycol) loop providing cooling to the winery processes. Figure 4.81 details schematically a typical chiller plant set up for a winery.

Whilst this is a simplified detail of the layout and components that make up a packaged glycol chiller plant (with evaporative cooling), it indicates all the major energy consuming components. Significant electrical energy is necessary to power the compressors, pumps, fans and control and actuation devices.

Multiple compressor units offer better operating performances over single compressor chillers, especially at part load conditions. Additional performance benefits are realised through step or VSD controlled compressor operation. Rejection of heat at the condenser is via water or air cooling. Water cooled systems either utilise a cooling tower or packaged evaporative cooler. There are two common forms used in the industry; induced draft or forced draft. An induced draft system uses a large axial fan at the top of the tower to draw air counter flow to the water whilst forced draft towers have fans on the air inlet to push air either

Fig. 4.82 Packaged glycol chilling on skids with detail of major power using components: **a** open-drive, reciprocating compressor, **b** evaporator centrifugal fan, **c** evaporator coolant pump

counter flow or cross flow to the movement of the water. Forced systems use centrifugal fans which require more fan power, thus power used compared to induced draft towers. Evaporative-cooled chillers are essentially water-cooled chillers in a box. The condenser, water sump and pump, etc., are all integral to the chiller. Whereas a water-cooled chiller, a separate cooling tower, condenser pump and site installed piping is required. Evaporative-cooled chillers offer the ease and savings of air-cooled chiller installation whilst providing performance comparable to water-cooled chillers. Evaporative-cooled chillers require makeup water (water/glycol mixture), water treatment and drains. Smaller wineries with small to medium sized chiller plants may use air cooled chillers avoiding the need for cooling towers, condenser pumps and condenser piping which can offer substantial capital savings, along with significant space saving. Figure 4.82 shows a standard installation in a medium sized Californian winery. This system is a 20 ton unit with open-drive, reciprocating compressors with external capacity control,

Fig. 4.83 Differing chiller plant locations; in a covered service space, adjacent to the winery building (exposed site), internal space with open roof access

Fig. 4.84 Forced air cooled condensers mounted on winery roof due to space restrictions

connected to a flooded glycol chiller providing cold glycol to the winery's fermentation tanks and barrel storage room. The flooded glycol chiller has improved heat transfer coefficients coupled with a more efficient use of the heat exchanger surface and a wider range of operating temperatures. The system also utilises a programmable logic controller (PLC) which provides precise control of compressor loading and unloading giving a much smoother system operation.

Due to the very low humidity encountered during the hot summer periods, a significant percentage of Californian wineries have opted for the packaged evaporative cooler arrangement. This is not always the case and in more humid operating environments, air cooled systems dominant. Due to the plant size, most wineries will have a large dedicated service area to accommodate the plant and ancillary equipment and pipework. Figure 4.83 depicts some other installation locations that are commonly set aside for chilling plant.

It is necessary to provide good service area access to permit periodic maintenance or equipment/component replacement. This may require the winery to offset a greater portion of the space for plant requirements to allow this access or to accommodate built in redundancy in the form of equipment duplication for crucial plant services. Figures 4.84 and 4.85 highlight this particular issue. The former,

Fig. 4.85 Temporary packaged glycol chilling with forced air cooling

a forced air cooled condenser unit was mounted on the winery roof due to space restrictions. In the other example, the winery was forced to rent a packaged forced air refrigeration plant to provide glycol chilling for the winery when their fixed installation was not in operation due to system failure. Operating this type of plant, particularly forced air systems, in confined areas is inadvisable. Poor heat dissipation can result in decreased system performance. Figure 4.86 shows an air cooled system in operation, with an IR image detailing the hot air exhaust through the casing louvers.

In a similar vain to the heat exchange surfaces of fermentors, when chilling at sub-zero temperatures, frost accumulation on the external surfaces of the glycol distribution network leads to additional energy usage. As water vapour condenses on the cold surface and changes to ice, significant energy is expended. Where possible, all pipework and fittings should be insulated. In certain circumstances, access for maintenance must be permitted and in these cases appropriate insulated casings must be used. Figure 4.87 shows some frost build up on a plate heat exchanger and glycol pump.

In a study of a Western Australian winery [4], 377,000 kWh of electricity was used in refrigeration (process and HVAC), which was calculated to be 0.35 kWh/l of wine produced and in a similar study of a Californian winery [28], 262,204 kWh of electricity was used in refrigeration, which was calculated to be 0.32 kWh/l of wine produced (process and HVAC).

In a study of the Sonoma Wine Company, a custom crush service provider in Sonoma County, California, Rosenblum [27] details the energy usage for refrigeration electricity and compares the usage against a baseline case provided by the California Sustainable Winegrowers Alliance (CSWA). The study goes on to show how savings were implemented, reducing electricity energy usage by 56% whilst production went up from 1.5 to 3 million cases. Electricity usage on refrigeration was measured at 1,860,000 kWh/year (0.138 kWh/l), whilst the baseline was suggested to be 840,000 kWh (0.062 kWh/l).

Fig. 4.86 Packaged glycol chilling with forced air cooling (*left*), IR image of the plant (*right*)

Fig. 4.87 Frost accumulation on exposed metal component surfaces

In a study by Cotana and Cavalaglio [10] approximately 336,000 kWh/year was used in an Umbrian winery in Italy by the refrigeration equipment, equating to 4.2 kWh/m^2.

Compressed Air/Inert Gases

Compressed air (and inert gases) is a very important service for many types of winery equipment, the two most important being supply to pneumatic presses during harvest and in-house bottling lines. Compressed air has been estimated to be between 4 [28] and 7% [15] of the total electricity use in a winery that has a bottling plant. Compressed air systems have a very low overall system efficiency, typically from start to end-use can be about 10%. This low performance, however,

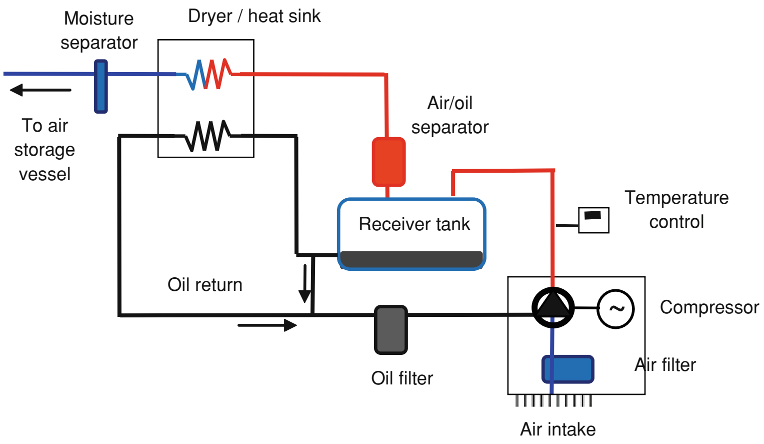


Fig. 4.88 Schematic detail of a compressed air system

Fig. 4.89 Various winery air compressors

is offset by the flexibility provided. Figure 4.88 details a simple schematic of a compressed air installation for a winery. The two main electricity using items of equipment are the compressor and air drying/cooling unit.

The type of air compression system employed by a winery varies considerably. The small section of systems shown in Fig. 4.89 demonstrates that the size, type,

Fig. 4.90 Small mobile air compressor in a small winery operation

location and state of the systems vary from winery to winery. In very small wineries, small mobile air compressors may be preferred (Fig. 4.90).

The compressor is probably the most important part of any compressed air system, of which there are essentially three basic types; reciprocating (piston) and rotary screw (which are positive displacement) and centrifugal (non-positive displacement or dynamic), which can be further divided into being oil flooded or oil free, water or air cooled and single stage or multistage compression.

Reciprocating air compressors cover a broad range of output capacity, ranging from 0.75 to 450 kW, with compression ratios of 5–6. Rotary screw compressors range from 20 to 250 kW with a maximum practical discharge pressure limit of 16 bar. Centrifugal compressors work in stages, with compression ratios of up to 3 at each stage, although inter-stage cooling (air or water) is necessary. There are many different variables used to calculate the energy load, but based on a baseline scenario, an average of 300 W power is required per litre per second of compressed air delivered at a 2.2 bar pressure differential [8].

In many wineries, electrical power used in producing compressed air can represent a significant proportion of the winery's electrical requirement, typically 5–6%, equating to approximately 5 kWh/m^2/year [28]. In an Australian study, compressed air represented 56% of the 15% electrical energy used in the plant room, or just over 8% of the winery's total electrical requirement. There were two 37 kW compressors installed [4]. In addition, some larger wineries will often have onsite nitrogen generation. These systems compress air and collect the nitrogen through a peculation system, after which it is stored for distribution around the winery.

Pumps

The pump is probably the most common piece of equipment found in the winemaking facility, whether it is a separate component or part of a larger packaged system. In the winery, the pump can be classified as either being fixed or mobile. Fixed systems

Table 4.1 Typical electricity use for various pumping activities (adapted from Neelis et al. [19])

Pumped fluid	Winery activity	Electricity benchmark
Hot water	Malolactic fermentation	0.5 kWh/1,000 l of wine fermented
Cooling water	Chilling processes	5.8 kWh/1,000 l of wine produced
Hot water	Barrel cleaning	0.8 kWh/1,000 l of wine produced
Hot water	Bottling	0.07 kWh/1,000 l of wine bottles washed
Waste water	Water treatment	0.7 kWh/1,000 l of wine produced
Waste water	Pond aeration	16 kWh/1,000 l of wine produced
Ground water	Water extraction from well	3.1 kWh/1,000 l of wine produced
Wine	Wine process steps	1.5 kWh/1,000 l of wine produced

Fig. 4.91 Various examples of winery fixed pump stations (**a** waste water pumps; **b** glycol pump; **c** pond transfer pump; **d** fire protection pump; **e** irrigation pump station)

cover a wide range of applications, primarily for building or site related fluid transfer activities. Mobile pumps are primarily used to move the wine product (juice, must, wine and waste) between the various stages of the winemaking process. Neelis et al. [19] describes typical electricity benchmark values equated to pumping wine, water, cooling water, hot water and wastewater in the winery (Table 4.1).

Fixed Pumping Stations

As previously mentioned, fixed pumping systems cover a wide range of applications within the winery environment. Given the different types of activities, the

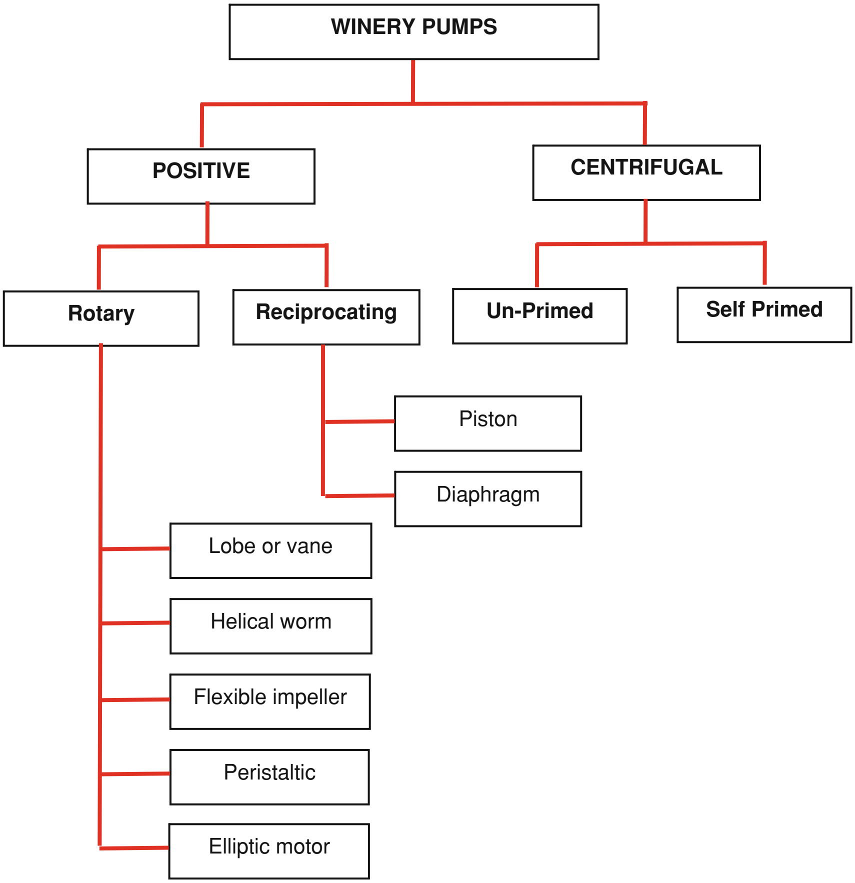


Fig. 4.92 Classification of pumping systems used in winemaking (adapted from Boulton et al. [7])

Fig. 4.93 Must pump

Fig. 4.94 Rotary lobe positive displacement pump with front plate and lobes removed

size and operating performance of the pumping system varies significantly. Typically, in a winemaking facility, fixed pumping stations are used in HVAC pumping systems, storm and waste water pumping, irrigation systems, frost protection systems, domestic water pumping, fire protection, aeration systems, boosting systems, condensate, water features, nutrient dosing systems and so on. Fixed pumping systems were calculated to be 4% of a Californian winery's electrical load, equating to 5 kWh/m^2/year [28] (Fig. 4.91).

Mobile (Wine) Pumping Units

As previously stated, pumps are used in wineries to move juice, must, waste and wine. These wine products, however, contain significant amounts of acid, so any pump used for wine must be made of corrosion resistant materials. A variety of pump formats are available to meet the requirements of different winery applications [21]. In basic terms, wineries use either centrifugal or positive displacement pumps. Figure 4.62 illustrates the classification of pumping systems used in winemaking (Fig. 4.92).

Positive Displacement Pumps

A positive displacement pump is any pump where the liquid is moved through the pump in discrete cavities. Except for centrifugal pumps, essentially all winery pumps utilise some form of positive displacement action, of which the rotary lobe and helical rotor are preferred in larger wineries. The rotary lobe pump displaces the wine by means of two intermeshed lobed rotors. Because of their ability to move suspended solids, lobe pumps are great for pumping over fermentations. The progressive cavity pump is also a positive displacement pump and uses a helical rotor

Fig. 4.95 A small flexible-impeller positive displacement pump

Fig. 4.96 Centrifugal pump

inside a helical cavity to create a moving void in which the wine is displaced forward. The progressive cavity pump is preferred in medium sized wineries.

Positive displacement pumps are generally preferred for moderate flow rate applications (up to 1200 l/min) when operating under high pressure heads. Figures 4.93, 4.94 and 4.95 illustrate some of the positive displacement pumps used in the modern winery.

Centrifugal Pumps

Centrifugal pumps are very common in larger wineries, but they are really only useful for tank-to-tank wine transfers and when large flow rates (up to 500 gpm) against moderate pressure heads are needed. They move wine by using a rotating disc-impeller, which can be either magnetically coupled or directly coupled.

Fig. 4.97 Diaphragm pumps

Magnetically coupled pumps are more expensive than direct coupled pumps. They are not self priming and sometimes getting these pumps started is difficult. On the other hand, magnetically coupled pumps have long, trouble free operation and they do not have shaft seals to leak air and oxidize the wine (Fig. 4.96).

Diaphragm Pumps

Although not electrically operated, diaphragm pumps are very useful for wine transfers and in particular, bottling transfer. Air diaphragm pumps run on compressed air rather than electricity and move wine via the compression and expansion of membranes, or diaphragms, inside the pump housing. They are fairly easy to clean and maintain, gentle on the wine and can move fairly large volumes of fluid. Diaphragm pumps are only suitable if the facility has a compressed air system. From an energy usage point of view, given the inefficiencies in compressed air systems, the pumping output to electrical energy in is quite low in comparison to direct electrical pumping. One consequence of not using electricity, however, means that the hazard of electrocution or ignition of ethanol spirit in the winery is reduced (Fig. 4.97).

Due to the level of wine transference required, a standard winery will have upwards of ten mobile pumping stations ready to operate at any time (Fig. 4.98). In many situations VSDs (Variable Speed Drives) coupled to the pumping sets is common practice to reduce electrical consumption.

In a study looking at the energy used to transfer wine product within a Western Australian winery, transfer pumps used approximately 7800 kWh/annum, transferring 13,000,000 l of juice/wine, equating to 0.6 kWh/1,000 l [4]. The average pump size was 4 kW. Neelis et al. [19] suggest that the pumping of wine during the production stage is closer to 1.5 kWh/1,000 l of wine produced.

Gravity Transfer

In many situations, the electrical pumping consumption can be dramatically reduced if the winery is gravity-fed. Of course this is something that must be

Fig. 4.98 Multiple pumping units and VSD controllers

Fig. 4.99 Trefethen family vineyard winery designed on the gravity-flow concept (*left*) and upper level detail within the winery (*right*)

designed into the winery layout and is not applicable for all situations. Trefethen family vineyard winery (Napa, California) is an excellent example of an original gravity-flow winery design (Fig. 4.99). Harvested grapes were winched to the third floor of the building for crushing. Gravity carried the juice to the second floor for fermenting and eventually on to the first floor for aging. Far Niente (Napa, California) is another good example of a stone structure gravity fed winery (see Chap. 5). There are only a handful of new wineries, like Willakenzie Estate in Oregon, USA or the Alois Lageder winery in Northern Italy (Fig. 4.100), that fully embrace this concept. The winery must be designed across 4 Levels: Grape reception (highest), Crush pad/ferment floor, Blending area (optional) and Barrel room, bottling, and storage. In some situations, gravity flow can be incorporated into existing buildings without too much disruption.

The modern Alois Lageder winery is based on a novel circular, gravity winery design. Grapes, must and wine are transferred in the 15 m high ‘vinification tower’, eliminating the need for pumps and other mechanical methods and equipment. The fermentation tanks are set up in a circle equidistant from the centre. This ensures that grapes only need to travel a minimal distance before descending into this area, providing gentle, delicate handling, conserving the quality of the grapes.

Fig. 4.100 The modern gravity winery design in Alois Lageder (Italy) with a centralised distribution system (**a** grape reception hopper, **b** cap management and tank access level, **c** central distribution, **d** spilt level design)

In some small way, gravity can be used to augment winery activities. Figure 4.101 depicts a situation where gravity is used in transferring wine from one barrel to another. Of course, the fork truck operation must be factored into the energy usage.

HVAC

The size or complexity of Heating, Ventilation and Air Conditioning (HVAC) plant and equipment associated with any winery is very dependent upon the local climate. Seasonal and/or daily fluctuations in temperature and humidity necessitate that the winery has sufficient systems installed to ensure that wide fluctuations in the internal environment do not unduly affect the winemaking processes nor the building fabric or occupants within the building(s).

HVAC systems in wineries can be simply classified as being either building related or production related. Building related systems are generally designed according to requirements for occupancy comfort (temperature, humidity, air flow, etc.) and whilst not strictly HVAC, the needs of the sanitary appliances (hot water quality and quantity) may also be included under this heading. Production related systems are based on the needs of the winemaking processes and are designed according to the styles of wine being produced and the relevant codes of practice.

Fig. 4.101 Gravity barrel to barrel transfer

Fig. 4.102 Internal, ceiling mounted AHU with cooling coil and electric heating element (*left*), external air cooled condenser units (*centre*) and roof top packaged unit (*right*)

It is safe to assume, however, in many wineries, that not all HVAC systems are exclusive to building or production activities. In addition, in all HVAC terminology, refrigeration is an integral component of any HVAC system design. However, in the winery environment, refrigeration constitutes such a large proportion of the energy used that it is commonly thought of as a separate entity and thus is dealt with in a previous section.

Building Related HVAC Systems

Broadly speaking ‘building’ HVAC systems relate to space conditioning and hot water production in the winery. The modern winery is not just a facility based on production alone, but comprises administrative, hospitality, staff and technical support areas which all need to be serviced according to standards published by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) or the Chartered Institute of Building Services Engineers, for example. Once basic requirements of load have been determined, a range of different

Fig. 4.103 Variations in storage space cooling units (linear plenum chilling fan coil, single chilling fan coil and packaged fan coil unit)

Fig. 4.104 Fixed low level CO_2 extraction fan (*left*) and internal portable fan used to dilute CO_2 concentration within the winery (*right*)

systems exist that can be used to meet the winery's particular requirements. All systems can be classified as being either localised, partially centralised or centralised. However, the potential variation in HVAC design for any given winery is almost limitless and is beyond the scope of this publication. Figures 4.102, 4.103, 4.104, 4.105, 4.106, 4.107, 4.108 and 4.109 depict some of the more common installations found in the modern winery.

Production Related HVAC Systems

HVAC systems designed for production purposes are based on maintaining certain environmental conditions to ensure wine quality and providing a safe working environment for the building occupants. Like building related systems, they can be classified as being either localised, partially centralised or centralised and like building related systems, the potential range of potential systems is substantial. Figures 4.103 and 4.104 depict some dedicated production related HVAC systems.

Fig. 4.105 Textile ducting in barrel store

Fig. 4.106 Humidification control system and high level Stainless Steel distribution pipe with nozzles (misting)

Fig. 4.107 Wall mounted steam generator

In most installations, the equipment is located in situ, however, in some situations the main equipment is located remotely and the conditioned air is transferred to the space to be conditioned. In the majority of cases, metal ductwork (aluminium or galvanised sheet steel) is used, however, Fig. 4.105 details a winery that utilises a fabric duct arrangement. One benefit of this system is a gentler diffusion of air into the space, although the benefits in this context are unclear.

Fig. 4.108 Effect of humidification in barrel store at 80% RH and 15°C

Fig. 4.109 Pre-conditioning of winery air supply in Italian winery

There are four general types of humidification systems employed in wineries; misting system, misting system with integral fan, steam generation and mechanical foggers.

The most common system sprays very finely atomized water droplets (a mist) directly into the cellar atmosphere. These droplets evaporate almost instantaneously, creating what is called a 'dry fog'. These systems require an extensive installation of

the cellar to be ‘covered’ to ensure uniformity of the mist throughout the area to be humidified (Fig. 4.106). Generally, these systems consume much less energy than the steam generator-based designs. A second type and variation of the above is the use of fewer nozzles, but use of an integrated fan to distribute the fog throughout a wider area.

The most common form of humidification in the HVAC industry is steam humidification, but not so common in the wine industry Fig. 4.108). Steam is generated, cooled and distributed throughout the space in situ or using the building’s HVAC ductwork. The final system is the mechanical fogger. Water droplets are created by forcing air through nozzles under high pressure and combining with the water at the outlet. The air source can be a high velocity fan, but units can be designed with other sources of high-pressure air, with the air source usually integrated with the fogging nozzle in a stand-alone device. Clogging is usually not a problem, but noise pollution can be.

In a study of wineries in California, Smyth [28] determined that between 13 and 14% of the electrical load in the wineries was directly related to HVAC systems. These values did not include the indirectly supplied energy from boiler or chilling plant, but was based upon fans and pumps, electrical heating elements, localised heat pump/refrigeration units (wall, spilt, VRF), humidification plant, actuating devices and control systems. The winery HVAC electrical load was calculated to be 24 kW/m^2 and the annual total energy was 17 kWh/m^2 or 0.144 kWh/l of wine produced.

Many wineries utilise thermal mass or underground facilities to significantly reduce the cooling load of the facility. A very interesting design utilised in an Italian winery combines HVAC equipment and distribution systems with thermal mass ‘coolth’ storage. The winery was built into a cliff face with a 1 m wide space deliberately created between the building structure and cliff face. This space serves as a pre-conditioning chamber for the winery production HVAC installation. Figure 4.109 shows the AHU located with the space adjacent to the rock face.

Other Equipment

In the modern winery administrative, hospitality, staff and technical support areas can represent a significant proportion of the facility’s floor area. This can typically include equipment related to cooking and food preparation, beverage and snacks, sanitation and washing equipment, entertainment, office equipment, retail equipment, workshop and maintenance equipment. In a study by Smyth [28], 5–6% of a winery’s electrical energy usage was calculated to be represented in this grouping. Neelis et al. [19] suggest that around 6% of the total electricity use is used by office equipment and other equipment.

Miscellaneous

There are numerous ‘one-off’ items to be found within the modern winery, they include items such as UV insect killers, roller shutter doors, electric gates, fork

Fig. 4.110 Fork truck charger, electric security gates and UV insect killer

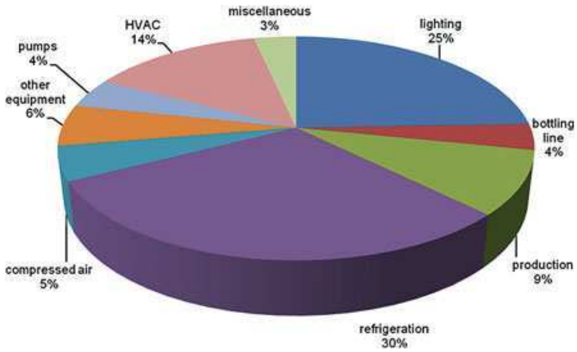


Fig. 4.111 Distribution of electrical usage within the Carneros winery [28]

trucks and lifting equipment, lifts/elevators and communication and IT servers (Fig. 4.110).

4.2.3.2 Electrical Power Distribution

The previous section details the various items of plant and equipment that require a substantial electrical load within the winery. The proportion of distribution of energy usage by each group varies from winery to winery. A study of two large Californian wineries by Smyth [28] determined the breakdown of electrical usage within each winery. Figures 4.111 and 4.112 detail the energy distribution for the Carneros and Napa Valley based wineries, respectively.

Whilst quite similar in proportions, there is a slight difference in production values. This is due to pumping. In Fig. 4.111, winemaking pumping is included in production. In Fig. 4.112 pumping loads are distributed throughout the facility. A study by Anon [4] on a Western Australian winery gives a more detailed breakdown of the electrical usage within the winery, as shown in Fig. 4.113.

In the Californian examples, refrigeration and lighting represent the largest single components of electrical usage within the winery. In the Australian example, electrical usage for refrigeration is greater than all the other demand loads combined. Lighting is much less, although this presented percentage may not account for all of the lighting load, which may be integrated into the other various space loads within the winery.

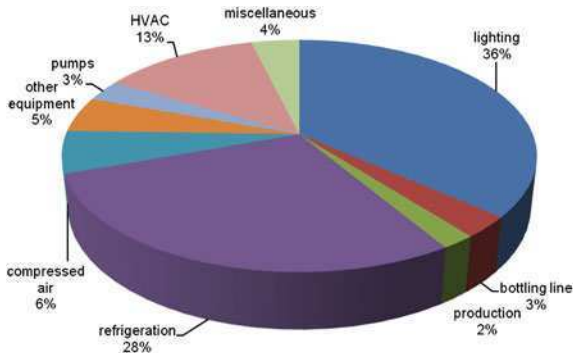


Fig. 4.112 Distribution of electrical usage within the Napa Valley winery [28]

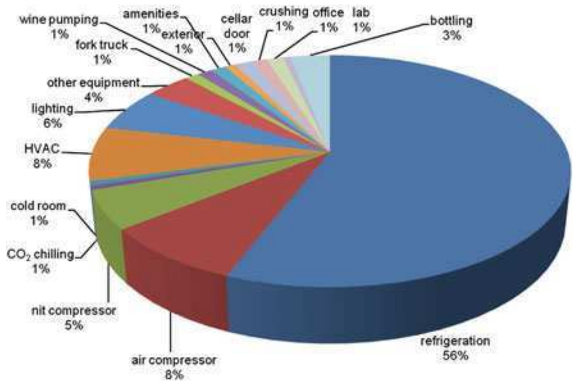


Fig. 4.113 A more detailed breakdown of the electrical usage within an Australian winery [4]

4.3 Energy Process Flows in the Winery

The modern winery can produce a wide range of different wine products, from dry sparkling to sweet dessert wines. However, the vast majority of wines fall under the heading of sparkling or still red and white wines. The various processes involved in the actual production of the wines have been detailed previously; this chapter presents the major energy requirements at the various stages of production.

4.3.1 Energy Process Flow for Sparkling Wines

There are four main methods of producing sparkling wine, as described previously, each having a very different energy requirement. The main methods are listed as:

- Carbon dioxide (CO_2) injection where CO_2 is injected directly into the bottled wine
- 'Charmat' where the wine undergoes the secondary fermentation in a bulk tank and is bottled under pressure

- 'Traditional method' or 'méthode champenoise' where the secondary fermentation takes place in the bottle. As the name indicates, this method is used in the production of Champagne and is more energy intensive than the previous two methods
- 'Transfer method' is similar to the 'traditional method' but following secondary bottle fermentation, the wine is transferred back into a pressurised tank again before bottling

Producing sparkling wines by the 'méthode champenoise' or 'transfer method' in the modern winery requires a significant amount of automation and energy input. Figure 4.114 illustrates the typical process diagram for 'méthode champenoise' and indicates the various energy inputs into the production line.

The process, and indeed the energy used, in producing sparkling wine differs from that of still wines. Karousou et al. [17] conducted a study on the energy consumption in sparkling wine vinification based on two different sparkling wine producers (Caves Pupitre and Cava Covides). They calculated that 0.0298 kWh was used in the production of 1 litre of sparkling wine from pre-fermentation to disgorgement.

Stage 1: Harvest and Pressing

Harvesting and pressing for sparkling wine production typically takes place a few weeks earlier in comparison to other wine styles. For the most part, electricity is the dominant form of energy used, although some activities are conducted outside so gas, for example, in fork trucks may be used in conveying the grapes from bins to hoppers. The processes of collection, sorting, transfer, de-stemming, crush and press all differ according to any number of variables, so it is very difficult to present one value that covers all. Neelis et al. [19], based on a range of wineries propose that at receiving, 5.08 kWh/ton of grapes received is used for unloading and 1.76 kWh/ton of grapes received for pumping and moving the grapes. For pressing, 10.69 kWh/ton of grapes is used and 3.86 kWh/ton of grapes for pumping, but these values were based on still wine pressing and may be slightly higher as there are several press stages (cuvee, talle and press) involved in sparkling wine production. Smyth [28] determined that the electrical input to a 10 ton ($\sim$10 m^3) bladder press through a total press cycle was 5.62 kWh, equating to approximately 0.56 kWh/ton of grapes pressed. This study did not include the substantial compressed air input from the dedicated supply. A basic rule of thumb can be used to estimate the power from a press cycle, approximately 10–15 volumes of air per 10 m^3 per litre pressed.

In sparkling wine production the various varietals and 'growing' blocks tend to be processed separately and stored in separate tanks and do not necessarily meet until blending. Figures 4.115, 4.116, 4.117, and 4.118 depict the stages of harvest from collection to press at Domaine Carneros, California.

For most sparkling producers picking is done by hand but energy is still expended in the mechanisation of the grape collection and delivery to the winery. In some instances, the travel distance can be significant. Once the grapes arrive at winery the bins are off-loaded, weighed and sent to the press. Sometimes,

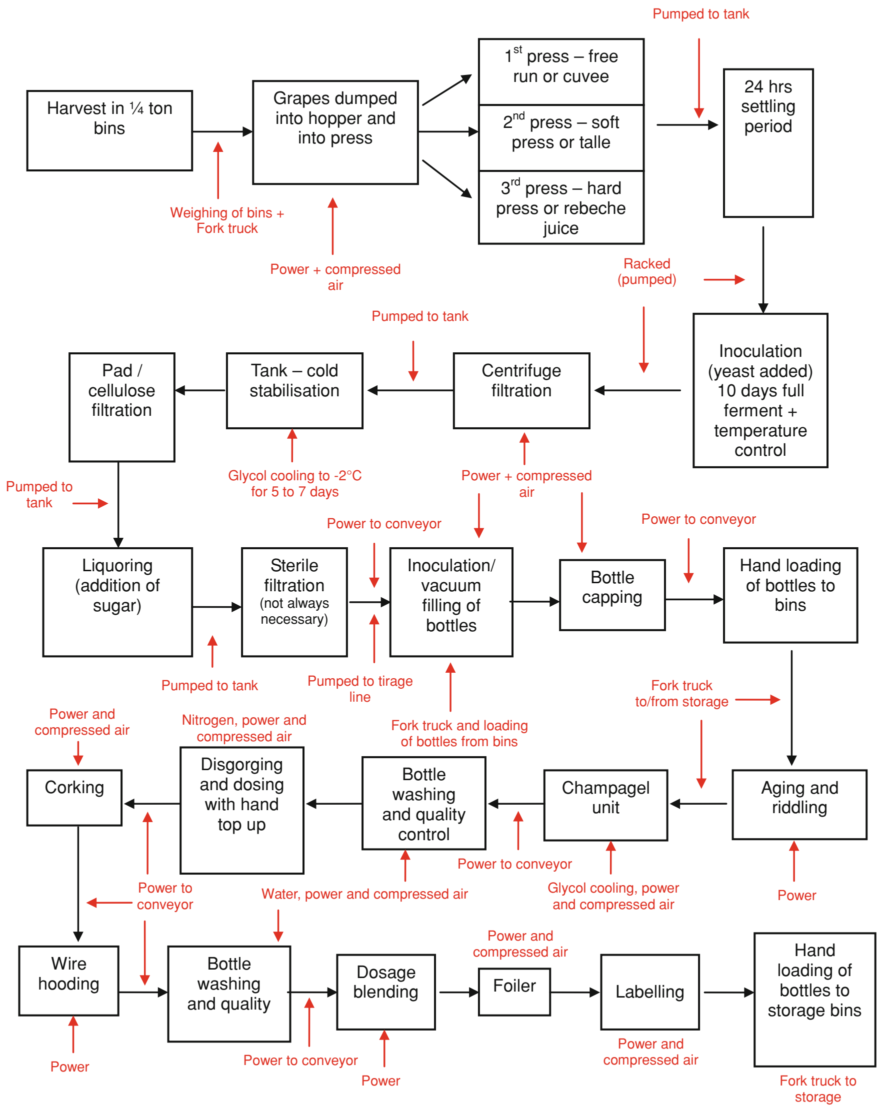


Fig. 4.114 Typical flow process diagram for 'méthode champenoise' sparkling wine

the quantity of grapes arriving can be greater than the processing capability and thus grapes can sit for a period of time before pressing. Picking in the morning can reduce the potential for grapes to overheat but sometimes it is necessary to store the grapes indoors in a conditioned space to prevent overheating. This can have an impact on the energy usage of the HVAC and refrigeration plant.

The grapes (Pinot Noir) are now dumped into the press. In this sequence of figures, the grapes are loaded into a hopper/chute above the press. Once the press is

Fig. 4.115 Hand picking (cool early morning) with mechanical collection at the Domaine Carneros estate vineyards

Fig. 4.116 Mechanical delivery and weighing at Domaine Carneros

Fig. 4.117 Dumping Pinot Noir grapes into the press hopper and washing bins

full, the pressing can begin. In this example, a large 10 ton ($\sim$10 m^3) membrane press is examined, using compressed air and electricity. The total electrical rating for the entire press unit is 17.4 kW.

From an energy usage perspective, the process begins with the hydraulic closing of the press doors. The electric motor rotates the press barrel by 180° and the 'free run' is allow to collect in the tank below (Fig. 4.119) and can be used as an indication of the maximum pressures for the cuvee. After the 'free run' has

Fig. 4.118 Chute into press and full press

Fig. 4.119 Free run and first press juice followed by pumping to tank

ended, the membrane is lightly compressed to 100 mb (10 kPa). The barrel is again rotated by two full revolutions and left for a period of 3 min. This sequence is repeated in increments of 100 mb up to 1.2 bar or more depending on the winemaker. At the end of this process, the cuvee stage ends and the juice is pumped to tank storage (Fig. 4.119). The next stage is talle, which begins with two full revolutions of the barrel. The membrane is again inflated, this time beginning at 400 mb, and is continually increased by 100 mb in 2 min intervals up to a pressure of 1.6 bar where upon the collected Talle juice is pumped to tank storage. The final press, the Press, begins following up to five full revolutions of the barrel. The membrane is again inflated, this time beginning at 1 bar and is continually increased by 200 mb in 1 min intervals up to a pressure of 2 bar. This juice is the lowest quality and in some wineries it immediately goes to a pre-chilled tank for storage so that the un-fermented juice can be sold off to another producer. The pressing stage ends as the membrane deflates and pomace removal begins. The hydraulic doors open and the barrel continually rotates for a period of 4 min. The pomace falls out of the barrel into an auger which transfers the pomance to a collection point (Fig. 4.120). Excluding the compressed air input, which is substantial, the total monitored electrical input for the entire press, lasting nearly 2.5h, was determined to be 5.62 kWh or 0.562 kWh/ton.

Fig. 4.120 Collection of pomace

Fig. 4.121 Dumping Chardonnay grapes into the press

Of course the process of collection, delivery and pressing is the same for the Chardonnay grapes (Fig. 4.121). The process described is typical, but individual wineries based on any number of factors may operate a completely different procedure and thus have a very different energy demand as evidenced by differing press cycles.

Stage 2: *Tank Vinification Processes*

Following harvest, tank or barrel vinification processing takes place. For sparkling wine this can mean diversification between the cuvee/talle and the press.

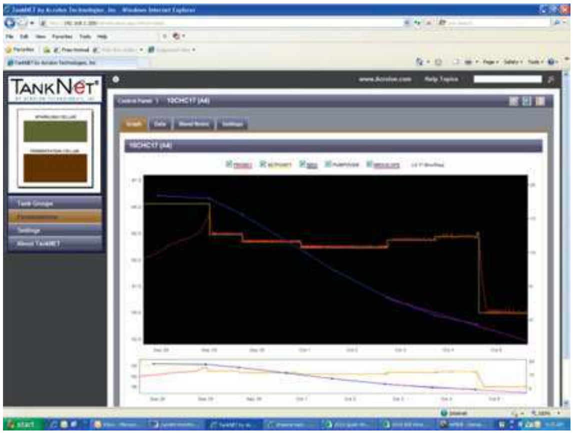


Fig. 4.122 Screen shot of TankNet and temperature and Brix variables for a sparkling Chardonnay tank

In many quality sparkling wine producers the press is sold on and therefore is stored in the tank at a temperature less than 9°C to stop spontaneous fermentation. The main processing for sparkling wine is described as 24 h settling (cold settling), fermentation at set temperature, post ferment clarification, cold stabilisation, blending, fine filtration, racking, liquoring and sterile filtration and then inoculation. Many of these processes are common to still wine production and are discussed in Sect. 4.3.2. There are some small differences however, be it in the number of different activities and therefore energy expended. In pumping, for example, some of the energy used for common processes may differ slightly. Karousou et al.'s [17] study calculated that 0.0016 kWh/l of sparkling wine was used in cooling for pre-fermentation cold treatment, together with 0.0088 kWh/l in cooling during tank fermentation and 0.0054 kWh/l in cooling for clarification and stabilisation. Other activities in sparkling wine production during vinification such as blending and liquoring require relatively small energy inputs.

Temperature control is crucial in the sparkling wine vinification process and good monitoring and thus response is necessary to produce the style of wine required by the winemaker. Although manual monitoring and control is common, many larger producers use monitoring/control software which provides more accurate feedback and control. Figure 4.122 is a screen shot of TankNet, a proprietary software package, which gives the winemaker real time output of the monitored variables. In this example, the actual temperature and Brix are plotted against a predetermined Brix curve and cooling regime for a sparkling Chardonnay tank.

Stage 3: *Tirage*

After the wine has gone through primary fermentation the wine is ready to be bottled and go through the second alcoholic bottle fermentation which can be a manual or automated process. In a larger sparkling wine producer, a three phase 6 kW load would be a typical power requirement for an automated tirage line. This is quite low as the line would typically only require power to the vacuum pump on

Fig. 4.123 New bottles placed onto beginning of tirage line

the wine supply line, vacuum bottle filler, capper, conveyor equipment and control instrumentation. Other utility services such as compressed air, water and waste streams are necessary. Figures 4.123, 4.124, 4.125 and 4.126 detail the process at Domaine Carneros, California.

A small 900 W vacuum pump is shown in Fig. 4.124. This pump provides the vacuum conditions in the wine supply line to the filling equipment to ensure near vacuum conditions in the bottle during fill. This minimises disruption in the fill process ensuring a rapid, smooth fill reducing damage and oxidisation of the wine. The now filled bottle is checked to monitor wine levels and, if necessary is manually topped up. The bottle now moves to the capper where it is sealed with a crown cap similar to that used on beer bottles.

After capping the bottle moves along the conveyor where they are manually packed into the bins ready for storage.

Stage 4: *Storage and Riddling*

Following tirage, the now bottled wine goes through secondary fermentation in the bottle. Once the second fermentation is complete, and the sediment begins to form in the wine, in a process known as autolysis, the wine is stored for a given period (minimum of 9 months but typically between 3 and 5 years), depending on the final taste of the wine. The temperature that the bottles are stored at in these stages is crucial and wineries employ significant air conditioning to ensure constant conditions. During the first few months the wine should be held at a constant 15–18°C with a few degrees lower thereafter. Depending upon the size of the winery and thus the storage capacity, the cooling load may be significant during this stage.

In European winemaking practices [19], the process characteristics for second fermentation (charmat) for sparkling wine is typically 16–20°C for up to 360 h.

Fig. 4.124 Quality control, vacuum filling and manual top up (*left*) and vacuum line pump (*right*)

Fig. 4.125 Capping equipment

For bottle fermentation, as in the champenoise method, energy usage is estimated at 0.0019 kWh/l. This value is based on air circulation only as storage is often in caves or cellars. In modern, above ground storage spaces, this value may be much higher due to external heat transfer (cooling and heating). Karousou et al.'s [17] study of Spanish wineries calculated that 0.0057 kWh/l was used in cooling for second fermentation for sparkling wines.

Whilst temperature control may be the overriding energy requirement at this stage, lighting is noted to be the second. This load is very much dependent upon

Fig. 4.126 Manual transfer to bin storage

Fig. 4.127 Air conditioning fan coil unit in bin store

the lamp selected and their duration of operation. Lighting quality is generally not important in the storage area, but lighting is necessary to allow for various warehouse/cellar activities. In most situations, sodium vapour/discharge lamps (and luminaires) are preferred due to their efficient 200 lumens per Watt. However, they have a poor colour rendering index, as shown in Fig. 4.127, and the characteristic monochromatic yellow light is obvious. Colour rendering is not a requirement in the storage spaces and the output can be less detrimental to the stored wines. Figures 4.128 and 4.129 show individual sparkling wine bottles being stored in cellar/caves.

Following aging, the bottle is rotated, either manually or mechanically, in a process called remuage, to allow the lees to settle in the neck of the bottle. The act of remuage was traditionally carried out by trained 'riddlers' on wooden racks or pupitres (Fig. 4.130). This act is still conducted by many smaller producers, but is

Fig. 4.128 Cave storage of sparkling wine (reproduced by kind permission from Schramsberg Vineyards)

Fig. 4.129 Wooden racks for remuage in cave (reproduced by kind permission from Schramsberg Vineyards)

very labour intensive. In larger, modern wineries, this task is carried out by an electrically powered riddler or gyro-pallet (Fig. 4.131) and is often now referred to as ‘riddling’.

A typical automated riddling machine operates with cages containing up to 500 bottles. The unit runs for approximately 1 week and is capable of rotating up to four cages. A relatively small 1.3 kW motor is sufficient to step rotate the cages through a relatively simple gearing arrangement. Whilst the electrical rating may be high, given that there may be many of these cages in rotation at any given period, the intermittent action ensures that the overall load is relatively low.

Stage 5: *Disgorgement and Bottling*

The final stage begins with disgorgement. In the modern winery this is fully automated, although batch processing is still practiced by some smaller producers. From a utility perspective, a lot of different processes and thus services are

Fig. 4.130 Remuage by a trained 'riddler'

required. Typically the majority of the energy input is electrical and is usually supplied via a dedicated three phase distribution board (Fig. 4.132). Including all the major items of equipment, the typical load could be in the region of 50 kW. The bottling line may also need smaller, hand-held portable equipment and therefore a number of three phase and single phase outlets are necessary at strategic locations along the line.

In addition to electrical power, the sparkling bottling line requires connections to hot and cold water, steam lines, compressed air lines, wine storage, monitoring and control systems and waste streams.

The caged bottles are moved from the riddling rack, via fork truck, to the disgorging/bottling line. The riddled, capped bottle is placed into a food grade glycol bath (anywhere between −10 and −30°C) to freeze the top of the bottle neck containing the lees. This condition of the sediment in the neck of the bottle is checked across an illuminated table before the bottle is placed neck down into a moving conveyor so that the bottle neck is fully immersed in the glycol bath. Figure 4.133 shows loading of the bottles onto the specialist champagel unit, capable of processing 1,500 bottles per hour. The Champagel group produce units that can process between 300 and 16000 bottles per hour, depending upon the application.

The initial act of disgorgement (bottle freezing) is the most energy intensive portion of the bottling process. Significant amounts of energy are required to ensure that the glycol is maintained at the correct temperature. The champagel unit in Fig. 4.134 utilises a dedicated vapour compression refrigeration unit, with the waste heat dumped to an external evaporative cooling tower. In addition to refrigeration, glycol pumping and air movement, motors are required for the moving conveyor and bottle distribution equipment. A typical 'stand-alone' automated bottle freezing unit, such as the presented champagel unit, combined

Fig. 4.131 Automated riddling units at Domaine Carneros, California

Fig. 4.132 Dedicated power supply to the bottling line

with the disgorging unit was measured to use 0.027 kWh/l [28]. This is somewhat higher than the 0.0082 kWh/l taken from the Amethyst report [19] which stated the energy assumed in the disgorgement and yeast removal process in sparkling wine production via the champenoise method. Karousou et al.'s [17]

Fig. 4.133 Bottles being manually transferred to the champagel unit

Fig. 4.134 A champagel unit

study calculated that 0.0083 kWh/l was used in cooling in disgorgement and yeast removal. These values are bound to vary from winery to winery based on variables such as production rates, operation and age of equipment, etc. Figure 4.135 depicts some of the important components of the champagel unit.

Figure 4.136 shows the bottles being mechanically removed from the glycol bath, inverted (left above the bath for 10 s to allow excess glycol to drip off) and placed unto the conveyor. Figure 4.137 gives a close up of the frozen neck.

Following chilling the bottles are placed onto a moving conveyor, washed to remove any remaining glycol from the neck and the cap removed. The decapper, shown in Fig. 4.138, slightly tilts the bottle neck towards a hopper where a tool removes the metal cap. The pressure in the bottle pushes out the ice containing the lees into the hopper. The bottle is quickly corked to maintain the carbon dioxide in

Fig. 4.135 Components of the champagel unit (glycol pump, refrigeration unit and evaporative cooling tower)

Fig. 4.136 Neck frozen bottles from champagel to main bottling line

Fig. 4.137 Close up of frozen lees at neck of bottles

Fig. 4.138 Decapping and disgorging

Fig. 4.139 Liquor addition and corking

wine, but just before corking some liquor (le dosage) is added and some top up may be necessary to maintain the liquid level within the bottle (Fig. 4.139).

Once the cork is inserted, a top capsule and wire cage are inserted to secure the cork in place. After the dosage blender, where the bottles are given a 360° revolution (or shaken) and a brief wash, the bottles move on to the foiler and labeller (Figs. 4.140, 4.141, 4.142, 4.143).

Figure 4.144 illustrates the measured electrical demand by bottling line activities for a Californian sparkling wine producer [28]. It is evident that refrigeration and electric hot water production for in line bottle washing represent the largest electrical requirements, equating to almost 75% of the total electrical requirement. Over a typical process period, through a fully automated bottle line, the electrical requirement was measured to be 0.049 kWh/750 ml bottle processed or just over

Fig. 4.140 Wire hood installation

0.065 kWh/l (in some instances there may be a time break between disgorging and final labelling and packaging processes).

In smaller or high quality producers, most of the above process is carried out manually. Figure 4.145 shows some of the equipment used by a smaller sparkling producer. The capper requires a compressed air supply only, as does the disgorger. The corker/wirer unit also requires compressed air, but requires a 3Ø power supply. This particular unit, a Durfo—TGF 500, with a production rate of 500 bottles per hour (0.37–1.5 l) requires a 1.5 kW 3Ø power supply.

Figure 4.146 shows a manual 'champagne' foil applicator, bench top model and the image on the right illustrates the operation. The first position folds the capsule into four pleats and the second position smoothes the capsule to the bottle and cork profile. The unit requires an air pressure of 4–5 bar.

The bottling and finishing process for some premium products or large bottles (magnum, etc) can also be largely done by hand. Figure 4.147 shows label attachment being done by hand using a small automated gluing unit.

In most wineries, the bottles are manually packed into cases. However, this process can be labour intensive and can involve back injuries in the physical task of lifting and palletising each case. In some wineries, the bottle packaging process has been automated. In simple terms there are two main systems employed in the selecting, moving and positioning of the bottles into a box; robotic 'pick and place' and 'soft drop'. Pick and place technology uses a computer controlled robotic arm to grab the bottles off the conveyor, transfer and lower them into their appropriate positions within the box. Sparkling bottles are more delicate and therefore require a greater level of care. In the bladder system the pick-up head moves down over the neck, wire hood and foil of each bottle and instead of fingers grabbing the bottle, a soft bladder inflates around the bottle neck, providing a gentle, but secure hold from which the bottle(s) is lifted and moved to the box. Soft drop simply allows the bottles to 'drop' off the conveyor into a pre-positioned box. The term

Fig. 4.141 Dosage blender by rotation (*left*) and shaker (*right*)

Fig. 4.142 Foiler and labelling

'drop' does not actually imply that the bottles are in freefall, but rather the box is brought up to meet the bottles, resulting in a smooth, easy motion. Figure 4.148 shows a vacuum suction unit used in a sparkling wine producer to move the boxed product. The unit is relatively low power, requiring a 2 or 3 HP motor to provide a sufficient vacuum to lift the boxes.

Once the bottling and packaging process in finished, the finished product is either shipped off directly or put into storage. Storage can be either on site or in a purpose made storage facility. Off-site storage has economic benefits to the winery but from an energy usage perspective, the efficiencies of air conditioning by bulk may be off-set by the additional transportation. Figure 4.149 depicts a typical bottle storage warehouse, whilst Fig. 4.150 shows Cava storage in a Spanish winery cellar.

Fig. 4.143 Boxing and finished product (Domaine Carneros)

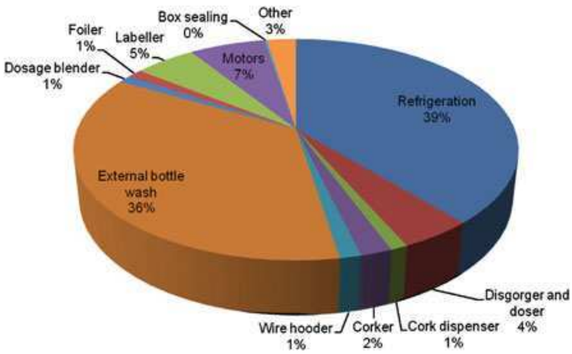


Fig. 4.144 Measured electrical demand by bottling line activities for Californian sparkling wine producer, Domaine Carneros [28]

Karousou et al. [17] presented a study on the energy consumption used in storing sparkling wine (finished cava) in cellars. From their study of wineries in Spain and Southern France, they conclude that the energy usage for active cooling (maintained under 16°C) depends significantly on the climate and cellar location and structural thermal insulation. They suggest that the typical cooling requirement for a 1,000 m^2 cellar (capable of holding 100,000 l of wine) is between 0.6 and 1.5 MWh/year, equating to 0.006 and 0.015 kWh/l stored.

4.3.2 Energy Process Flow for Still Wines

The energy required in the process stages for producing still wines differs significantly from that used in sparkling wine production and thus requires a different

Fig. 4.145 Capper (*left*), disgorger (*centre*) and corker/wirer (*right*)

Fig. 4.146 Manual 'champagne' foil applicator (*left*) and application process (*right*)

Fig. 4.147 Manual label application with small automated gluing unit

Fig. 4.148 Vacuum suction unit used in packaging

Fig. 4.149 Bottling storage warehouse

section to review the energy demands. However, whilst all still wine energy requirements can be broadly grouped together, there are a number of differences in the production of red or white styles. Whilst it is difficult to demonstrate all the variations used in making the wide range of wine styles in this category,

Fig. 4.150 Old Cava storage in a Spanish winery cellar

Figs. 4.151 and 4.152 detail a very generic form of still wine production (red and white, respectively) and the commonly applied energy inputs.

Of all the service requirements in the still wine production process, electricity is by far the largest energy input. Physical handling of the product, both into the process line and from the process line, is mostly via electric or gas fork truck vehicles. Significant amounts of compressed air is required, primarily for pressing, punching and various activities in the bottling line and some heat via combustion equipment may be necessary in certain circumstances. Electricity, however is used throughout the process for the major chilling, pumping and mechanical activities. Figures 4.153 and 4.154 detail the approximate electrical proportions used in the Californian wine industry for red and white wine production, respectively.

Comparing the proportions of energy usage of white to red still wines [11, 15], aging, storage and fermentation represent the biggest differences. Proportionally more energy is used during the fermentation process as cooling for white wines in comparison to red wines. In Karousou et al.'s [17] study, they calculated that 0.158 kWh of cooling and 0.0467 kWh of heating was necessary per litre of white wine from initial cold settling to bottling, including washing of barrels, tanks, etc. Values for pressing and filtration were not included in the study. For red wine production, under the same criteria, Karousou et al. [17] calculated that only 0.106 kWh of cooling was needed whilst 0.0757 kWh of heating was used per litre of red wine.

Stage 1: *Harvest and Pressing*

Both red and white still wine production requires a common harvest to de-stemming process, similar to the processes and thus energy requirements to sparkling wines (Sect. 4.2.1). Following de-stemming, however, the processes diverge. Red wine production requires that the grapes 'soak' and ferment with their skins before pressing whilst white wine is usually pressed before ferment. Figure 4.155 details images of the red wine process from collection to tank.

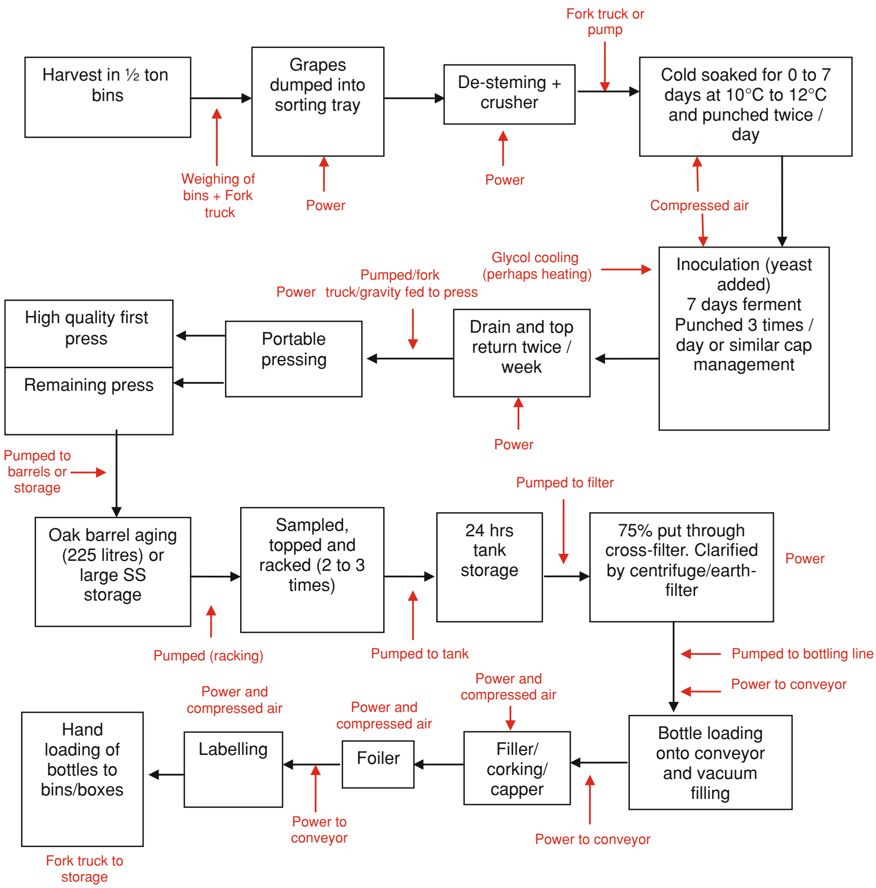


Fig. 4.151 Flow processing diagram for still red wine

In Fig. 4.155a, the grapes on arrival are stored in the ferment hall (to prevent overheating), before being ‘fork trucked’ to the de-stemmer/crusher (Fig. 4.155b). After this process all unwanted elements are removed (Fig. 4.155c) and the crushed grapes are transported to the vats for cold soaking (Fig. 4.155e). Figure 4.155d shows the addition of a sulphur solution (to remove unwanted microbial action) and dry ice to produce rapid cooling and create a CO_2 surface barrier to prevent oxidisation. The dry ice can be seen sublimating on the surface of the grapes in the bin. A dry ice pelletizer will require typically 0.05 kWh to produce 1 kg of dry ice, excluding additional losses from storage and transport. During the batch vat filling process, the vats are pre-cooled before filling and the cooling process is continued for days to ensure colour extraction without an unwanted spontaneous ferment. Some wineries use pumped transfer of the crushed grapes opposed to batch transfer. This is only an indicative example of the stages involved. Many wineries have their own particular methods in processing the

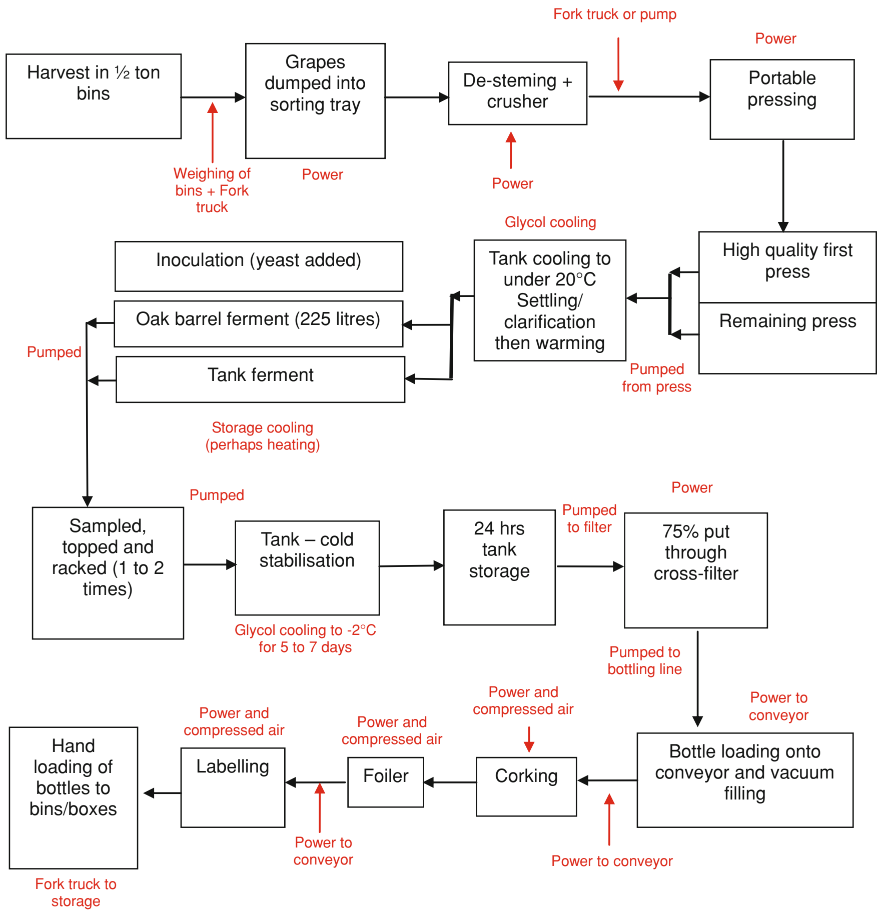
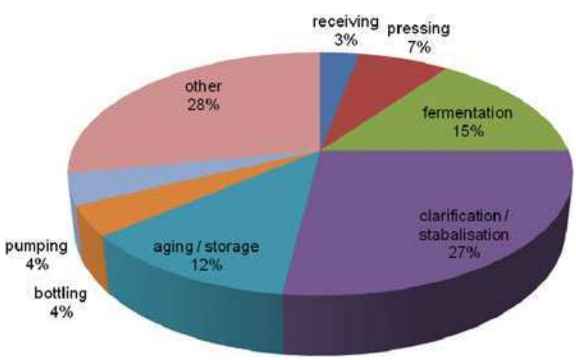


Fig. 4.152 Flow processing diagram for still white wine

Fig. 4.153 Electricity in red wine production (adapted from Galitsky et al. [15])



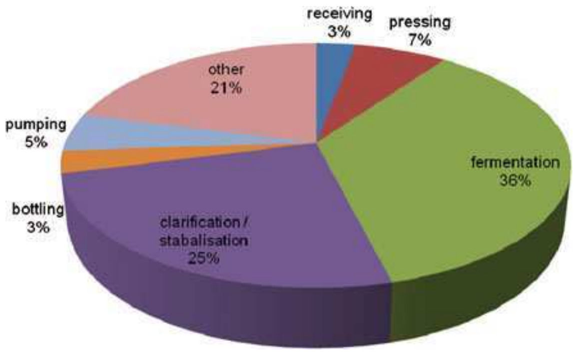


Fig. 4.154 Electricity in white wine production (adapted from Dugger [11])

grapes. Figure 4.156 shows a large rotating red wine vinification facility. Each tank is rotated twice through 360° every day of the 5–6 day ferment period. Whilst the size of each tank is large, due to the extended period of operation, a small single phase motor is capable of rotating the tank which is largely offset by the energy used in other tank cap management processes.

Obviously, if vat cooling is used there is significant energy usage. Having insulated vats results in most heat generated having to be removed by refrigeration but there are many variations. Figure 4.157 details rows of similar vats in two different wineries. Both are receiving crushed grapes and the vats have been pre-chilled. The major difference is location. In the internal vat installation, losses and gains from the local environment are reduced.

Certain styles of white wine and rose production may also require the grapes to sit on the skins for a number of hours to soak and extract some colour. Figure 4.158 shows an arrangement whereby the harvested/crushed grapes are dumped into the vat and left to sit for 3–12 h before being gravity fed into the press below. This set up can reduce interim fork truck and pump transference activities, although it does require a dedicated facility and hence is usually only utilised by bulk producers of this particular style of wine.

Both types of wine may undergo a pre-fermentation cold maceration. The actual energy input is based on the fruit temperature on arrival and cold maceration temperature along with losses from tank to the surrounding environment. A cold treatment temperature of 5–10°C is typical for most wine and 12.5°C is typical for the other wine types. Cold treatment is usually maintained from overnight to many days for red wine and up to 12 h for the other wine types, [19]. Harvesting at night or harvesting in cooler regions can significantly reduce the energy used in the cold treatment process. Whether pressing occurs before or after cold maceration, approximately 10.69 kWh/ton of grapes is used for pressing and 3.86 kWh/ton of grapes for pumping during this time [19]. Karousou et al.'s [17] study calculated that 0.021 kWh of cooling is necessary per litre of red and white wine for cold treatment from 25 to 12°C using glycol cooling at 7°C. In most white winemaking processes, following pressing but before inoculation, the must undergoes cold static settling. Karousou et al. [17] calculated that 0.037 kWh of cooling is necessary per litre of white wine for cold static decantation at 5–7°C (Fig. 4.159).

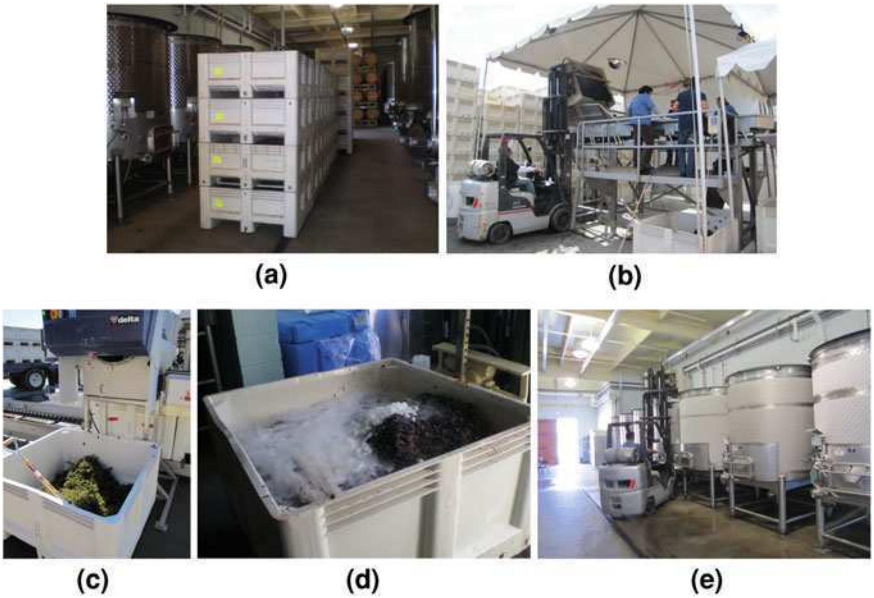


Fig. 4.155 Pinot Noir processing from collection to tank (Domaine Carneros) **a** grape storage **b** de-stemmer/crusher **c** unwanted elements **d** sulphur solution and dry ice **e** cold soaking

Fig. 4.156 Rotating red wine vinification facility (*inset*: rotation motor)

Another process that can occur before fermentation in red wines, to maximise colour extraction, is the process of thermal vinification. This typically requires a temperature of 65°C for a duration of 9 h [19]. This is a process more commonly used in lower quality wines, but may result in significantly higher energy usage.

Stage 2: *Tank/Barrel Vinification Processes*

Following harvest, tank or barrel vinification processing takes place. These can be described as inoculation and fermentation, cap management, racking and pump transferring activities, clarification and filtration.

Fig. 4.157 Pinot Noir cold soak inside (*left*) and outside (*right*)

Fig. 4.158 Overhead storage vats

Fermentation is a process that is dependent upon a number of variables; wine type, style, temperature, duration and sugar content, to name but a few, and therefore the processes and activities and thus energy usage, is highly variable from winery to winery. During the fermentation process, heat is produced and requires that a certain level of cooling is used to remove the excess heat. In a reasonably accurate rule of thumb, for each Brix of grape sugar, sufficient heat is generated to raise the temperature of the must by 1.3°C, assuming no heat loss [29]. In isothermal conditions, where refrigeration and ambient conditions match heat generation, the juice fermenting at a rate of 1 Brix/day equates to approximately 0.00775 W/l [7]. This value does not account for the 5–10% of the heat generated that is lost via the fermentation gas. Boulton et al. [7] also provide a more accurate profile of heat release rates for red and white wines, coupled with peak rates.

Fig. 4.159 Chardonnay prior to pressing and ready for juice transfer to tank

However, heat loss is present and takes places via 3 main mechanisms:

- Carbon dioxide exhaust. Around 10% of the heat may be removed in this way in reds and 5% in whites
- Heat loss through the surfaces of the vessel in a sealed container
- Heat loss through the walls and base of the vessel and exposed must surface in an open container.

Of course in many regions of the world, fermentation takes place at a time when ambient temperatures may be high and thus natural heat loss is insufficient to maintain the must at its required temperature. Cooler fermentations require the wine in the tank to be maintained at 12.5–15.5°C (55–60°F) whilst in a warmer ferment, the tank is maintained at 18.5–21°C (65–70°F). It is therefore necessary to actively cool the must in the vessel.

In red wine, the must is fermented for 7–10 days at a temperature between 20 and 30°C but typically from 25 to 27°C. During this period, colour is extracted from the skins. The skins and solids in the must will float to the top of the fermentation vessel, forming a cake from which the carbon dioxide cannot escape and only a thin layer of juice contacts the skins. This cake is broken down by breaking the cake by the methods indicated previously. Pumping, stirring/mixing or 'punching' all require a level of energy input. Karousou et al.'s [17] study calculated that 0.039 kWh of cooling is necessary per litre of red wine for alcoholic fermentation with maceration at temperatures of 15–26°C. Figure 4.160 shows a punch down compressed air system used for cap management in Pinot noir wine production.

Following fermentation, the wine is drained from the vat (Fig. 4.161) and pumped to another SS vat whilst the pomace is transferred manually into bins and taken to press. Figure 4.162 depicts a winery where this process is fully mechanised. In some wineries, this secondary press wine is combined back with the drained wine, in others they are kept separate. Figure 4.163 shows the berries being loaded

Fig. 4.160 Compressed air punching

Fig. 4.161 Pinot Noir wine draw off and berry collection

Fig. 4.162 Fully automated mechanical bin transfer system

Fig. 4.163 Pinot Noir press and the residual marc

Fig. 4.164 Mechanical conveyor to remove residual marc from press

Fig. 4.165 Large scale mechanical overhead collection

Fig. 4.166 Pumped barrel filling

into the press and the residual marc after the press process. Some wineries have adopted a fully mechanised approach and use conveyor systems to move the wet pomace to the press and dry marc to waste (Fig. 4.164). Figure 4.165 shows a large scale automated facility with overhead dumping system.

The wine is now left to settle, perhaps 24 h. It is then typically racked off and sent to barrel storage to undergo malolatic fermentation, either by pumped transfer or gravity, depending upon the winery set-up (Fig. 4.166).

White wines are typically fermented at cooler temperatures than reds. For white wines, fermentation takes place for anything from 2 to 45 days at a temperature usually between 7 and 18°C (45 and 65°F). The lower the temperature, the longer the fermentation continues and the more fruity the wine. Fermentation vessels that get too warm produce off flavours and can get stuck. Hence, cooling and good temperature control are important in white wine fermentation. Karousou et al.'s [17] study calculated that 0.054 kWh of cooling is necessary per litre of white wine for alcoholic fermentation at temperatures of 12–16°C.

The most common mechanism used in tank temperature control is a double jacket (heat exchanger) stainless steel tank. A stainless steel 'wrap-around' jacket is welded unto the outside of the stainless steel tank (Fig. 4.167). Inlet and outlet ports are connected to the jacket so that the chilled water, or more commonly glycol, can flow in maximum contact with the wine must but all possibility of contamination is removed. There are many versions and sizes of these tanks in existence.

Typically half of the vessel surface is in contact with the 'glycol' jacket, with one-third of this value in the upper portion of the tank and the remaining two--thirds in the lower portion. This design helps prevent stratification within the tank, by ensuring the production of convective motion within the must. Boulton et al. [7] report that there have been minimal studies conducted on the heat transfer coefficients for jackets used in fermentors, but from their research values range from 12 to 60 W/m^2/°C.

Whilst the jacketed fermentor is the most commonly applied mechanism in cooling (or heating) the must/wine, external heat exchangers can also be utilised. External heat exchangers can be employed when a different cooling regime is

Fig. 4.167 White wine tanks with different heat exchanger designs

Fig. 4.168 Shell and tube heat exchanger

required. Figure 4.168 shows the most commonly used external heat exchanger, the shell and tube heat exchanger, in the winery. Other types include the plate heat exchanger, the spiral heat exchanger and the scraped surface heat exchanger.

Each form of external heat exchanger has its particular merits and application within the winemaking processes; shell and tube heat exchanger for general applications, plate heat exchanger for energy recovery applications, spiral heat exchanger for must cooling and the scraped surface heat exchanger for cooling wines close to their freezing point [7].

It is very important to maintain a uniform temperature distribution within the tank. Thermal inversion or single point temperature measurement can give the winemaker erroneous feedback and thus it is very important that temperature feedback is not limited or that a facility exists to actively mix the must within the tank periodically. During the fermentation period (and pre-fermentation cold treatment and cold stabilisation) a significant amount of electrical energy is consumed in the refrigeration plant to maintain glycol flow temperatures sufficiently low enough to maintain the desired must temperature. Generally, with lower glycol temperatures comes an increase in the proportional energy ‘chilling’ requirement. Glycol flow temperatures of −6°C (20°F) are sometimes typical.

Malolactic Fermentation

The heating requirements for malolactic fermentation (MLF) in tanks or barrels are based on the heating requirements from the ambient to the fermentation temperature and the conductive losses from the tank to the room. Many variations in temperature and duration exist, however, and are dependent on the winemaker. Malolatic fermentations are dependent upon wine conditions, bacteria activity and temperature. They can occur quickly and easily or may take an extended period. Often in the case of non-heated wine, MLF will also complete in the following spring when ambient temperatures increase. The room temperature in the case of malolactic fermentation in barrels is assumed to be 5°C above the fermentation temperature, optimised at 20°C. An energy input for heating the room and keep it a constant temperature was determined to be 0.067 kWh/l of wine fermented, assuming a period of 56 days for malolactic fermentation [19]. An additional 0.0019 kWh/l of wine fermented was determined for energy use for air circulation for wine fermented in barrels. Karousou et al.’s [17] study calculated that 0.029 kWh of heating is necessary per litre of red wine for malolactic fermentation at 30°C.

Tank pumping, racking, centrifuge and filtration are all common activities in this stage of the winemaking process and have been discussed in “Production”.

Clarification

Post ferment clarification is used to separate the clear wine from the yeast and other solids after fermentation. The most common techniques to clarify wine are racking, cold stabilisation, fining and filtering or a combination.

Racking is the oldest form of clarification and it involves siphoning off the relatively clear wine after the lees have settled to the bottom. Racking may happen once or more than once depending upon the winemaker. Frequent racking can injure the aroma of the wine and render it liable to become acidic. Aeration during this stage may be beneficial to some wine styles, and detrimental to others. Because the SO_2 content initially added is exhausted during fermentation, it is adjusted again at this stage to prevent spoilage and oxidation (Fig. 4.169).

Fining begins by stirring a fining agent into the wine that removes suspended particles in the wine before settling at the bottom of the vessel. The clarified wine is

Fig. 4.169 Positive displacement pump used in wine transfer

then separated off by racking. Over-fining should be avoided as it can result in thin wines that lack aroma complexity, flavour depth, viscosity and aging potential.

Depth or sheet filtration (previously presented in "Separation and Filtration") uses a thick layer of fine material to trap and remove small particles. Surface or membrane filtration passes wine through a thin film of plastic polymer with uniformly sized holes that are smaller than the particles. Sterile filtration uses micropore filters that are fine enough to remove yeast cells and bacteria to prevent further spoilage.

Cold Stabilisation

Cold stabilisation is used to remove excess tartaric potassium bitartrate acid. The process of cold stabilisation chills the wine down to about −4 to 0°C (25–32°F). The KHT acid crystallizes and is drawn off by racking. This can take several days or may be sped up through the addition of fine ground cream of tartar seed crystals. The contact process allows stabilisation to be accomplished in a continuous manner in 4 h with heat recovery between input and output streams. Karousou et al.'s [17] study calculated that 0.029 kWh of cooling is necessary per litre of red and white wine for cold tartaric stabilisation using glycol cooling at −10°C.

In a study by Dugger [11], the merits of insulation for tanks during cold stabilisation are presented. In the study, two white wines were traditionally glycol cooled in a tank with and without insulation and the energy intensities compared. The uninsulated tank required 0.317 kWh/l whilst the insulated tank required only 0.006 kWh/l. In the same study a comparison was made between traditional glycol cooled tanks against flash refrigeration techniques. Flash refrigeration or freezing is a process whereby the substance is subjected to cryogenic temperatures using liquid nitrogen or a mixture of dry ice and ethanol. In their study, the red wine getting cooled in the traditional tank, with no insulation, required 0.2 kWh/l, whilst the flash refrigerated red wine in the other tank only required 0.012 kWh/l.

Fig. 4.170 Cold stabilisation with external frozen condensation on exposed heat exchanger surfaces

Cold stabilisation through the crystal flow process is very energy intensive. Another method to remove excess bitartrate acid that has been investigated is electro-dialysis. Electro-dialysis is a membrane process driven by an electric current, moving the tartrate ions from the wine through a membrane to an aqueous solution. This technology was developed in Europe and is applied in wineries around the world. In trials, energy intensities of less than 8 kWh/US gallon have been recorded for both reds and whites [13]. On the downside there are issues relating to space, time and winemaking style, in addition to increased water consumption leading to increased wastewater treatment and associated energy costs. Moisture in the air surrounding the tanks results in surface condensation on the tanks and due to the very low flow temperatures, ice forms (Fig. 4.170). This change of state absorbs significant energy, changes the heat transfer characteristics, leading to an increase in the refrigeration load. The legalisation of bitartartate crystallisation inhibitors such as metatartaric acid or more notably CMC, offers an alternative to this energy intensive step.

Stage 3: *Storage*

Following clarification, the wine is stored and aged. Wine is stored at the winery but may be stored in an off-site warehouse. Storing requires a certain level of energy input. There are thermal control considerations but also activities such as racking, topping and maintenance must be considered. Maintaining an appropriate temperature is the biggest single energy requirement. Temperature controls the chemical reactions taking place in the wine and that has an impact on the wine quality.

In most wineries, the cellar is a warehouse in which the temperature and humidity is controlled. In many wineries, this means a dedicated air conditioning system. The amount of energy consumed however, can be reduced through good building design and operation. Temperature control can be achieved using cool night air with artificial cooling. In some wineries, the cellar may be underground in a purpose made structure or cave complex (Figs. 4.171, 4.172).

Fig. 4.171 Underground storage facilities

Fig. 4.172 Construction of winery caves into hillside in the Napa Valley

Underground storage can be also partially achieved using berming (Fig. 4.173). In this instance the building is built into a slope. This is really only applicable for new-build wineries and orientation and topography are natural considerations. However, even with berming, a significant proportion of the building's external surface still remains exposed. Good use of building materials and finish are extremely effective in reducing solar gain and insulating the storage space.

Figure 4.174 depicts a number of wineries using good levels of structure insulation (new-build and retro-fit) to maintain the appropriate storage temperatures whilst minimising the cooling load. Utilising reflective structure finishes is also a common methodology employed in reducing unwanted solar gain (Figs. 4.175 and 4.176).

White wines tend to be stored in (stainless steel) tanks and should be aged under cool conditions, generally 11–13°C (52–55°F) or cooler but never more than 16°C (60°F). Once the stored wine has achieved its storage temperature in the tank, the wine temperature can be maintained by ensuring that the tank storage space is maintained at a suitable set temperature using the air conditioning systems of the warehouse. In some novel situations, an unused/unfilled fermentation tank, supplied with glycol, may provide enough cooling to maintain the set room ambient temperature. However, in the vast majority of cases, forced air cooling units (with humidification when necessary) are used. Karousou et al.'s [17] study calculated that 0.017 kWh of cooling is expended per litre for aging and storing for red and white wines.

Fig. 4.173 Some examples of winery berming

Fig. 4.174 Good use of structural insulation in barrel room stores (new-build and retro-fit solutions)

Fig. 4.175 Light roof colour finish to reduce solar gain

Fig. 4.176 Light coloured sand on cellar roof to reduce solar gain and provide aesthetic benefits

Fig. 4.177 Innovative space cooling process using a tank's glycol cooling jacket

In an interesting example of ingenuity, where a space cooling facility is undersized, or the wine production facility has increased beyond the dedicated cooling system's capability, the tank's glycol cooling system can be 'hijacked' to provide an augmented cooling system. Figure 4.177 depicts an empty tank that has been deliberately cooled to produce an ice coating on the internal and external surfaces of the tank creating ice from condensation. Once coated, the ice is knocked off and a mobile fan used to blow air through the tank, producing a simplistic ice cooler.

In some cases white wines are kept as low as 4–7°C, but this presents a number of energy usage issues. It usually means that the tanks must be directly cooled by glycol chilling as it is not practical to maintain the ambient air temperature of the tank room at such a low value. Inevitably, 'coolth' loss will occur to ambient. The maintenance of 'coolth' with the tank can be significantly enhanced through insulated tanks. The wine is racked every 2–3 months while aging.

As previously stated, white wines are typically aged and stored in tanks, however, some white wines are barrel aged. Chardonnay is kept in barrels for 3–24 months but typically 6–9 months, stored in a room cooled to about 14–16°C (58–60°F). Many red wines benefit from being aged in barrels (although there are some exceptions). Red wines generally gain in quality and complexity by aging in oak barrels. Red wines are generally stored at temperature ranging from 7 to 21°C, or on average 15°C (59°F). Red wines may age up to 6 months for light red wines and up to 3 years for robust red wines in the barrel. Wine racking may take place every 2–3 months while aging. As wine ages, typically 2–5% by volume per year (on average 3%) of the wine is lost due to evaporation or ullage, sometimes referred to as the 'angels share'. This lost wine must be replaced otherwise oxidation or acetobacter spoilage may result. Barrels are topped with wine frequently with warmer dryer storage conditions requiring a weekly frequency and energy in

the form of pumping and fork trucks are used in the process. To keep the losses to a minimum, humidity levels within the barrel storage rooms is closely controlled. Most winemakers prefer levels of relative humidity at around 85%, lower levels increase the rate of evaporation and too much can lead to mould growth. Whilst fixed moisture control systems can be expensive, they do not require a large amount of energy to operate. "Production Related HVAC Systems" details some typical installed systems.

In the study by Neelis et al. [19] an energy usage of 0.00567 kWh/l was determined for the aging and storage of wine in barrels (based in natural caves or well-insulated rooms that do not require significant air conditioning) for air circulation and humidification only. Karousou et al.'s [17] study calculated that 0.017 kWh of cooling is expended per litre for aging and storing for red and white wines.

Rosenblum [27] in a study of the Sonoma Wine Company, details how radically altering the building infrastructure by having light coloured exterior surfaces, good structural insulation, evaporative cooling, passive ventilation and increased day lighting can make significant energy savings. In this study, the California Sustainable Winegrower Alliance (CSWA) suggests that wine storage cooling should be 0.0048 kWh/l.

Stage 4: Bottling

Bottling of red and white wines differs from the process described in Sect. 4.3.1. Wine is pumped to the bottling line, although in some cases this may be through a gravity designed winery. Before bottling, the wine is clarified to remove any solids remaining in the wine after aging. In some wineries only 75% of the wine is filtered so that some of the wine characteristics are retained when the wine is combined again. The filtration is normally through a cross flow or pad filter. For wines that have not gone through a malolactic fermentation process, the wine is filtered through a membrane, to make sure that no biological or bacterial activity takes place in the wine when in the bottle (Fig. 4.178).

Larger wineries tend to have their own in-house bottling facility, usually in a dedicated room. For others, this process may be outsourced. In other situations a mobile bottling facility may be used. In most situations, the bottling room is a quality controlled space, with a positive air pressure to maintain a slightly positive atmosphere to reduce dust ingress and good temperature control and air filtration to reduce the organism growth and thus contamination of the wine. Wine for bottling must be brought up to the correct temperature, typically 17°C. Temperatures outside of the range of 15–20°C will result in incorrect fill heights. Under temperature will result in over-filling upon storage at room temperature. Over temperature will result in under-filling and breach of trading standards.

Figure 4.179 depicts the process of a fully automated still wine bottling line. Firstly the bottles are assembled onto a bottle receiving table to be picked up by the conveyor. At this stage the bottles may be washed, but more commonly are just de-dusted by blowing compressed air into the bottle. The bottle then travels to a multi-spout wine filler, followed by the corker. The bottle then moves to foiling, which can be an automated or manual process. In a screw top seal, the bottle passes

Fig. 4.178 In-line membrane filtration before bottling

to a screw capper following the fill. In a corked/foiled bottle the next stage is to heat shrink the foil onto the neck of the bottle. Both the cork and screw sealed bottles now go to a rotary labeller which is capable of multiple label formats, including cigar bands and neck labels. The final process in the automated bottling line is the manual packaging of the bottles into cases and then on to the automatic case sealer.

Figure 4.180 shows a number of other variations to the bottling line. Not all wineries use a fully automated bottling line, as previously stated, some may use a combination of machinery or some may use simple bottling equipment such as simple siphon hoses, funnels, hand corking and labelling machines. Figure 4.181 is a bottling line used in an English winery and Fig. 4.182 details individual items of bottling equipment used in a very small producer.

In many situations it is simpler to utilise a mobile bottling facility. A typical plan layout of a mobile (truck) bottling facility is shown in Fig. 4.183.

The bottling facility is housed within a truck trailer of dimensions 16 m long, 6 m wide and no less than 4 m high. In addition to the internal working area, an extra 10 m radius is required at the rear of the trailer to permit packaging, palletising and fork truck activities. The power requirements for the mobile facility are typically three phase voltage on 60 amp circuits to serve the internal bottling equipment. A mobile bottling facility should include:

Fig. 4.179 Overview of an automated bottling line

Fig. 4.180 Other bottling line examples (Far Niente and EOS estate)

Fig. 4.181 Bottling equipment in a smaller English producer (bottle filler and washer)

- Bottle receiving table and conveyors (with VSDs)
- Bottle cleaner to remove carton dust, with speeds capable of 100 bottles/min
- Spout wine filler and corker, usually a 24 spout filler with a and four head corker, capable of 50–95 bottles/min
- A eight head spinner capable of 50–100 bottles/min

Fig. 4.182 A four head Bancroft vacuum bottle filler (*left*) and screw-top capper (*right*)

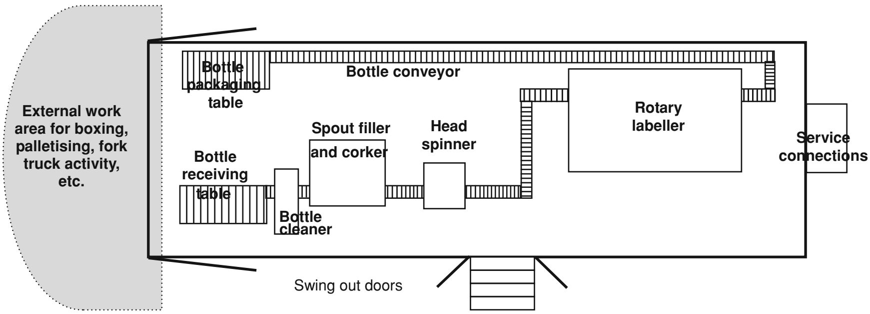


Fig. 4.183 Layout of mobile bottling facility

- Rotary labeller with up to three labelling heads for doing complicated, multiple label packages, as well as cigar bands and neck labels. Capable of 150 bottles/min
- Automatic case sealer, with clear or custom tape. Capable of ten cases per minute.
- Farley hot water generator (capable of producing steam on demand).

Figure 4.184 shows the external and interior operating spaces of a typical mobile bottling facility.

Generally, still wine bottling is much more energy conservative compared to sparkling wines. As there is less need for refrigeration, washing and other

Fig. 4.184 Images of mobile bottling line detailing the external work areas and compact internal spaces within the vehicle

activities, the energy requirement per litre of wine is significantly lower, as low as 0.002 kWh/l [28]. This is in agreement with the electricity benchmark as reported by the Amethyst Report [19] which estimated the bottling process for still wines at 0.0028 kWh/l. Fetzer Vineyards, based in Mendocino County, California, reduced their electrical energy input to their bottling line from 0.042 kWh/l in 1999 to 0.032 kWh/l in 2006 through good energy efficiency practice. These figures are higher than the benchmark, but Fetzer's values combine their sparkling and still production demand.

Once the bottling and packaging process is finished, like sparkling wine, the finished product is either shipped off directly or put into storage. Storage can be either on site or in a purpose made storage facility. Off-site storage has some economic benefits to the winery, but from an energy usage perspective, the efficiencies of air conditioning by bulk may be off-set by the additional transportation.

4.3.3 Energy Process Flow for Other Wines

Rose Wines

Rose wines are made from red grape varieties. Once a suitable colour has been extracted from the skins, the wines are made in a similar fashion to white wine production, having the same energy requirement.

Late Harvest Wines

Late harvest wines require that grapes are left on the vine to over-ripen so that the Brix levels are very high. Sometimes a rot called *Botrytis* can set in giving extra character. Once the grapes are harvested, the juice is fermented. From an

energy perspective, producing late harvest wines requires more refrigeration than say a Cabernet or Chardonnay. Firstly, the juice temperatures are held much lower prior to fermentation to hold off any spontaneous (unintended) microbial activity and secondly at the end of fermentation, the ambient temperature of the barrel room is lowered to encourage a slower yeast metabolism. Otherwise, the energy inputs scale with volume in proportion to that of the other wines.

Ice Wines

Ice wines are made from grapes that are left on the vine to ripen and raisin and picked during a frost when the grapes are frozen. Natural ice wines require a temperature lower than −8°C to be harvested. The grapes are then transported back to the winery and crushed. The water molecules in the grape are frozen and what is left is pure concentrate. In some examples, cryo-extraction is used to simulate the effect of a frost and grapes are picked earlier. Once frozen, the grapes are pressed. In another process, known as freeze distillation, concentration is still achieved but it occurs after fermentation. Given the intensity of the process, ice wine tends to be produced in smaller bulk quantities, requiring more intensive energy use per litre of wine produced.

Fortified Wines

There are many types and styles of fortified wine but all involve adding grape spirits to a still wine to increase the alcohol content to above 15%. The two most popular and well known fortified wines are sherry and port. In the case of port, the spirit is added before the still wine is finished fermenting. In sherry, the fortifying agent is added during the process. From an energy perspective, there is no significant increase in the energy input. Fortification does not require significant energy although additional time, and thus space conditioning, may be required in the aging process. On the other hand, the wines are more robust and need less cooling in storage. Generally port wines require a lower cooling load.

4.4 Other Energy Flows

Whilst much emphasis has been directed towards the wine production processes, many other energy using activities exist in parallel with winemaking. These are simply grouped into sanitation, building requirements and external services.

4.4.1 Winery Sanitation

Cleaning and sanitation is of the upmost importance for the modern winery and crucial to producing a quality product. There are many reasons as to why this is so.

Fig. 4.185 Typical hot water production methods (gas fired and electrical)

First and foremost is the legal requirement. Being a food product, the wine producer has a legal obligation to produce wine that is pure, wholesome and free from contamination. Then there is the customer consideration. The customer is buying a product and therefore maintaining good quality is paramount to earning and retaining consumer confidence. In addition, most wineries today are tourist destinations and therefore projecting a clean, aesthetically pleasing image of the winery contributes to a positive experience. Health and safety issues are more likely to arise in an unclean environment and maintaining a clean and sanitised winery operation is just good business practice. Finally, from an energy conservation point of view, a clean working environment is good for equipment and can maximise plant efficiency.

Winery sanitation activities can therefore be classified as being either directly related to the production process, bottle or barrel washing, for example, or maintaining a clean working environment such as washing floors. Other forms of washing, cleaning and sanitising equipment have been discussed previously in "Washing and Sterilisation". The vast majority of sanitation processes conducted within the winery are carried out using hot water, typically at 80–90°C. Most hot water is produced by some form of combustion process, as detailed in Fig. 4.185, with electricity used in lesser amounts, not usually for process hot water, but rather DHW needs. In addition, as is the topic of this book, hot water can be produced using solar input (Chap. 3).

Most wineries will have a dedicated hot water production and distribution network with hot and cold water outlet (hose) stations located at strategic positions throughout the facility. Figure 4.186 depicts a typical hot/cold water fixture.

Karousou et al. [17] from a rough evaluation of the average heat required to carry out cleaning of tanks and barrels for sparkling wine production in Spanish wineries, calculated that about 0.0936 kWh/year (water at 90°C) for each litre of sparkling wine produced is necessary. Figure 4.187 presents an adapted breakdown of the annual energy used for production washing requirements.

Karousou et al. [17] also calculated that 0.037 kWh of heating is necessary per litre of red or white wine produced for bottle washing at 70–80°C and 0.0097 kWh of heating is necessary per litre for barrel and tank washing at 70–80°C.

Fig. 4.186 Hot and cold water outlet for production processes

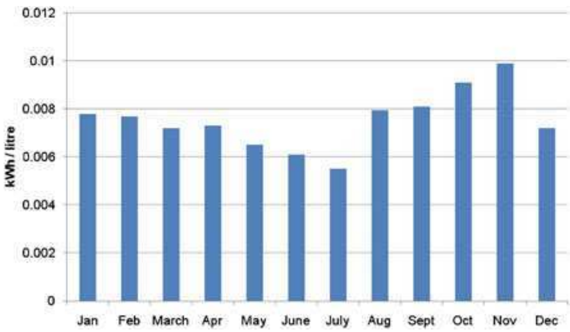


Fig. 4.187 Monthly energy used for production washing requirements (adapted from Karousou et al. [17])

In an Australian study [4], 47,000 l of LPG, converting to 313,000 kWh of energy, was used in hot water production (primarily for sanitation but some tank heating was included in this value) in producing 120,000 cases (1,080,000 l), which equated to 0.29 kWh/l of wine produced. A boiler efficiency of 90% was assumed in the conversion process [19].

In a study of the Sonoma Wine Company, a custom crush service provider in Sonoma County, California, Rosenblum [27] details the energy usage for hot water production (with caustic and citric bath) used in various processes and compares their usage against a baseline case provided by the California Sustainable Winegrowers Alliance (CSWA). The study goes on to show how savings were implemented, reducing energy usage by 66% whilst production went up from 1.5 to 3 million cases. Table 4.2 details the energy usage and comparison with the base case provided by the CSWA.

Table 4.2 Energy usage and comparison for various hot water activities in the Sonoma Wine Company (adapted from Rosenblum [27])

Process	Energy usage (kWh)		Energy benchmark (kWh/l)	
	Baseline	SWC (before)	Baseline	SWC (before)
Wine pre-heating	656,544	1,304,300	0.0486	0.0966
Barrel cleaning	234,480	512,925	0.017	0.038
Tank cleaning	319,479	527,580	0.0237	0.039
Line sterilisation	36,638	42,500	0.0027	0.00315
Floor/general cleaning	36,638	42,500	0.0027	0.00315
Total	1,380,000	2,429,800	0.102	0.18

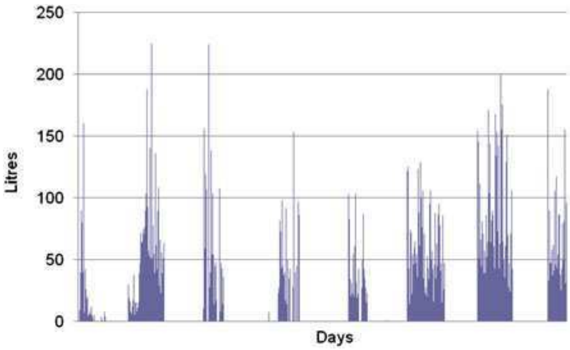


Fig. 4.188 Weekly profile in 5 min intervals of production hot water used in a Californian winery [28]

The CSWA suggested that the hot water usage for a winery of this size should be 40878 l/day (or 1.1 l of hot water per litre of wine produced). Rosenblum's [27] study determined that the SWC used 77,593 l/day before savings were instigated, relating to 2.1 l of hot water per litre of wine produced.

Figure 4.188 details the weekly profile in 5 min intervals from midday Wednesday to Wednesday of the production hot water demand during a non-harvest period for a Californian winery [28]. Typically, no production hot water is used at the weekend but due to bin washing and other activities in preparation for harvest, some water was used on Saturday and Sunday. Based on monitored records, 1510236 l of hot water was used over the year, equating to 1.86 l of hot water per litre of wine produced. LPG was used to generate the hot water and using a boiler efficiency of 90% [19]. The energy for process washing was calculated to be 0.083 kWh/l of wine produced.

Whilst variation in the process hot water demand exists throughout any given period, there is a particularly significant difference between the harvest and non-harvest periods. Figure 4.189 illustrates the difference in daily hot water demand during harvest and non-harvest periods for a Californian winery [28]. In the period preceding the harvest period, the average daily water usage was almost 2900 l during harvest this value jumps up to nearly 6,300 l.

Hot water for cleaning is required in a winery facility throughout the calendar year, but there are certain times when significantly more hot water is used in comparison to other times, namely pre-harvest preparation and a 2 month span

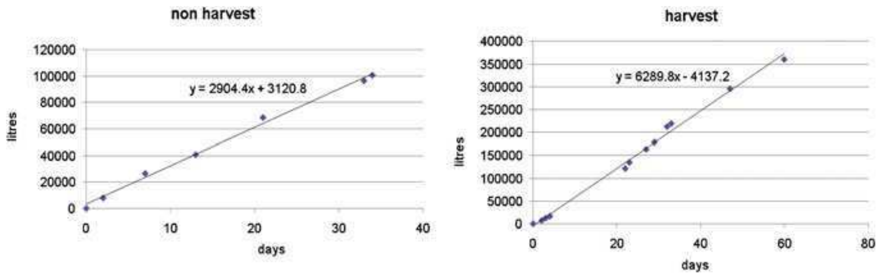


Fig. 4.189 Hot water usage between harvest and non-harvest periods in a Californian winery [28]

Fig. 4.190 Cleaning preparation for harvest; collection bins, pipe fittings and press hoppers

Fig. 4.191 Cleaning equipment after harvest and early vinification stages

during the harvest/ferment period. Figure 4.190 shows some of the common washing activities before harvest.

Following the main harvest period, although washing is continual throughout this time, a significant amount of hot water is expended in washing and cleaning harvest equipment prior to their storage. Figure 4.191 details the washing and cleaning of de-stemming and crusher components, bladder press components and berry receiving equipment and pipework.

Any time a tank transfer or rack takes place, all pipework and tanks are washed. This can be simply to remove material from the tank following the process, as shown in Fig. 4.192, or to provide a more comprehensive tank wash/sterilisation procedure. Figure 4.193 details a typical tank cleaning procedure.

The 'three' cycle wash is used to clean and sanitize a wide variety of winery equipment, in this example it is tanks. The wash cycles are an alkali wash (cycle 1)

Fig. 4.192 Open vat washing following racking and lees removal

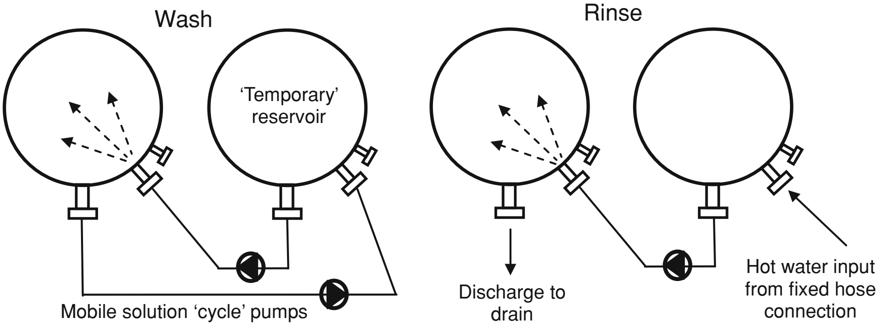


Fig. 4.193 Tank washing process (adapted from Storm [29])

followed by an acid wash (cycle 2) completed by rinses with hot water (cycle 3). During the wash cycle, the hot (alkali or acid) solution is stored in an adjoining tank, used as a 'temporary' reservoir. The solution is pumped into the tank to be washed from the reservoir under pressure through a spray nozzle. The spray water is returned back to the reservoir via a recirculation pump. Following wash cycles, the tanks are given rinses, using hot water. Hot water is stored in the reservoir tank and pumped into the tank under pressure through a spray nozzle. The water is allowed to discharge via gravity to the winery's floor drain. Even though the term used is three cycle, there are more than three cycles. A typical wash may start with a short debris rinse with water (couple of minutes), alkali wash (20 min), rinse (3 min), acidic wash (15 min) and final rinse (5 min). This can represent a significant amount of hot water with a typical flow rate of 0.6 l/s (Fig. 4.194).

In addition to barrel washing ("Washing and Sterilisation"), hydration of barrels is also very important. A typical process would require the barrel to be filled with 10–15 l of hot water (80°C) with the bunghole in place and the barrel rotated from side to side and top to bottom and left overnight allowing the barrel to completely swell and absorb moisture before filling. Soaking of all the external surfaces is also common (Fig. 4.195).

Fig. 4.194 Images of a tank washing process for a SS fermentor

Fig. 4.195 Barrel hydration

A winery will also use a sizable amount of hot water for domestic appliance requirements. All wineries will have sanitary appliances, culinary activities and working laboratory spaces. It is therefore essential that these areas have quality hot water. Like production hot water, this can be heated by a variety of ways. However, in many situations, the supply temperature is much lower, typically 35–65°C. Domestic hot water should be heated to at least 65°C periodically to minimise the risk of legionella, however water at this temperature represents a scalding risk and therefore mixing is necessary to bring the supply temperature down to 35°C. Sometimes, where appropriate, hot water is just heated to the desired temperature (Fig. 4.196).

In areas where water quality is poor, particularly in rural areas where water may be taken directly from a borehole source, energy input may not only be necessary in extracting the water but may also be necessary in improving the quality of the water.

Treatment of the water for all winery activities would represent a significant cost and therefore it is much more usual for a winery to only treat a proportion of the water

Fig. 4.196 Gas fired hot water production

used, as the vast majority of the water used is used for process washing and cleaning. However, it is necessary to treat a portion of water to maintain winery hygiene, protect downstream equipment and ensure overall product quality. A complete 'treatment train' is defined as being coagulation, sedimentation, filtration and disinfection. In the winery, given the size and space requirements, the term treatment usually just encompasses filtration and disinfection, with some conditioning relating to mineral content. This treatment system can be packaged or bespoke but most set-ups would normally include one or a combination of the following items of equipment; mechanical filtration system (slow sand filter, for example), reverse osmosis unit, chlorination unit, UV disinfection unit or water softening unit.

Whilst water treatment is essential in many wineries and requires a certain level of sophisticated power using equipment, the overall energy demand, whilst continuous, is relatively small and does not represent a huge proportion of energy usage in the winery (Fig. 4.197).

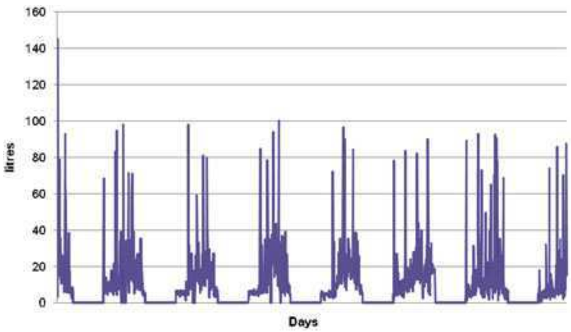
Treated domestic hot water is used in a variety of activities in the modern winery, from essential laboratory activities to normal day-to-day activities like culinary tasks and supply to sanitary appliances, as indicated in Fig. 4.198.

The variation in hot water supply applications generally means that there is a constant, if variable, hot water demand throughout the occupied hours of the winery, and generally every day throughout the year. Figure 4.199 details the weekly profile in 5 min intervals from midday Wednesday to Wednesday of domestic hot water demand during a typical week for a Californian winery [28]. Based on monitored records, 971,594 l of hot water (at 38°C average) were used over the year, equating to 140 l of hot water m^2 year. As the winery is open every

Fig. 4.197 Water treatment plant (UV disinfection unit and dosing equipment)

Fig. 4.198 Laboratory equipment sanitisation (*left*) and washing utensils and glasses in the kitchen (*right*)

Fig. 4.199 Weekly profile in 5 min intervals of domestic hot water used in a Californian winery [28]



day of the week, there is no lull in the weekly profile of hot water demand. LPG was used to generate the hot water and using a boiler efficiency of 90% [19], the energy for domestic hot water production was calculated to be 3.1 kWh/m^2/year.

Fig. 4.200 Wine tasting and hospitality spaces

Fig. 4.201 Winery machine shop

4.4.2 Building Services to the Other Spaces

Aside from the production spaces, processes and systems necessary within the modern winery, significant energy is used in providing thermal comfort, lighting, powering and servicing all of the other administrative, retail and support spaces within the facility. Many of the energy requirements for these activities have already been discussed in previous sections, however, it is important to note that they can represent a sizeable amount of the energy used in the facility.

Figure 4.200 shows some images of the hospitality spaces, now common in many winery facilities, which can range from small rooms to cater for guest wine tasting activities to large halls or auditoriums to stage large events. Figure 4.201 shows a winery machine shop. Whilst not always in constant use, these spaces are an important part of the winery to ensure continued operation. Machine shops usually have a wide range of tools and equipment, ranging from small hand tools requiring a few 100 W to large three phase fixed equipment such as lathes and welders that may require up to 20 kW. Neelis et al. [19] suggests that the electricity use for other equipment (offices, kitchens, etc.) can represent 6% of the total electricity use.

Fig. 4.202 Projected yeast images and background music in the Alois Lageder cellars (reproduced by kind permission from Alois Lageder)

Some wineries have interesting, if unique, energy requirements in what would be considered areas outside the normal winemaking activities. Figure 4.202 shows yeast images projected onto a wall in the Alois Lageder cellar using a data projector. In keeping with bio dynamic principles, images of Saccharomyces yeast cells are accompanied by music to assist the aging of the wines in barrels. The music is Johann Sebastian Bach's sixth Brandenburg Concerto, but it is greatly reduced in speed (a minute is stretched into an hour), to provide a harmonious drone in the room, sometimes rising and sometimes falling in tone.

4.4.3 External Services

In terms of external energy usage that is not covered by vineyard activities or directly connected or fixed to the winery, there is very little that has not been directly discussed in any of the previous sections. Several items of equipment, activities and services still exist however, that still require a form of energy input. These remaining energy requirements may be grouped as; transportation systems that operate in and around the winery but are not classified as haulage or vineyard vehicles and external building services that are not directly connected to the building's network and landscaping.

Landscaping of course can be used to reduce energy usage in the winery environment, trees planted for shading or wind sheltering, plants used to improve moisture retention or trans-evaporation and thus yielding a cooling effect but all too often in modern winery, landscaping is an energy drain. Most modern wineries have a hospitality operation and in keeping with an aesthetically pleasing environment, the vistas around the winery are landscaped to provide a particular theme. The upkeep of this landscape therefore requires a certain level of energy, whether it be equipment such as lawnmowers, chippers, chainsaws, etc. or irrigation and pumping requirements or in features like dramatic effect lighting or fountains and other water features (Fig. 4.203).

Transportation, from a functional operating point of view (not to be confused with entertainment vehicles), can be broadly categorised as fork trucks (lifts). Fork

Fig. 4.203 Landscaping energy demand

trucks are used extensively throughout the modern winery, to load and unload vehicles, move bins and tanks, stack barrels and shift equipment, supplies and finished products. Fork trucks can be classified according to the engine type, work environment, operator position and specific characteristics, such as tyre type or maximum grade. In the modern winery, typically there may be a range of different types but most will have electric units with cushion or pneumatic tyres and internal combustion units (LPG or diesel) with cushion or pneumatic tyres. Electric aerial aisle lifts and powered hand trucks and pallet jacks may also be used.

In electric fork truck selection, battery charge-life is important; with current batteries being able to operate up to 8 h before recharging is necessary. System voltages are normally 36 or 48 V, with a 48 V system having more speed whilst a 36 V system has a longer operating time. Fork trucks either operate through a DC or AC motor, with DC units having a slightly better performance through a lower RPM torque and AC units lower in cost and requiring less maintenance [22] (Fig. 4.204).

In the study by Smyth [28] the energy used by fork trucks was divided been the propane and electrically powered vehicles. The energy used was calculated to be 0.05 kWh (fuel equivalent) per litre of wine produced for the propane units (2 of) and 0.01 kWh/l of wine produced for the battery powered units (4 of). In the study by Neelis et al. [19], forklifts were assumed to use approximately 0.028 kWh (fuel equivalent) per litre of wine produced (Fig. 4.205).

In addition to the expected vehicles typically found in the winery environment, due to an increase in wine tourism, many wineries are investing in transportation systems, dedicated to moving winery visitors through their facility permitting a level of controlled access to production areas to view the winemaking processes. These vehicles require energy and in many cases, an electric input is preferred. Figure 4.206 depicts a couple of examples used in some modern wineries.

There are a number of external building services that, whilst part of the winery infrastructure, are not directly connected to the building's network. External portable heating and food preparation equipment would represent the largest grouping of energy usage under this heading. Gas patio heaters have today become a normal sight in most bar and restaurant external spaces. Whilst there are many forms and sizes, a standard gas patio heater will typically consume 0.857 kg/h of

Fig. 4.204 Fork truck charging and aerial lift

Fig. 4.205 Winery transportation

propane. When this is multiplied by the number of units and duration over a year, this can represent a substantial energy usage. Smyth [28] estimated that patio heaters consumed between 10 and 15% of the total propane used by a winery over the period of a year. It was acknowledged that the winery did have a significant external entertainment space (Fig. 4.207).

4.5 Energy Benchmarking

Energy benchmarking is a mechanism that allows a facility (winery) to compare and contrast the energy operating performance of individual plant and services or an entire process, or even a full facility against a common metric that represents ‘standard or optimal’ performance. As benchmarking is used to compare across different systems it must consider two important characteristics. First, because they

Fig. 4.206 Visitor wine train and aerial cable car

Fig. 4.207 Patio space heater

are applied to plants or sectors of different sizes and outputs, the metric used should be irrespective of plant size. This is accomplished using intensity, which measures energy use per unit of output. Second, the tool should be applicable to a wide range of facilities in order to increase the robustness of the analysis and, therefore, should be able to compensate for differences in production (e.g., product mix and climate) at similar facilities.

In the wine industry there are a number of energy metrics available, but the more commonly applied metrics are based on a standard energy unit, typically the kWh, against a volume, weight or area. In Europe this is typically represented by kWh/l of wine produced, kWh/m^2 of winery floor area or kWh/ton of grapes processes/crushed. In the US, the same principle metrics are used, using imperial measurements.

Benchmarking, done properly, is a tool that allows the winery management to evaluate and compare their systems, processes and plant against the accepted

Table 4.3 General winery activities and equipment and associated energy indicators and benchmarks

Process Description	Benchmark metric[a]			Reference
	kWh/l	kWh/m^2	kWh/ton	
Total vineyard and winery energy use				
German study	2.41			Elmar et al. 11
South African study	2.34			Elmar et al. 11
Hungarian study	0.55			Elmar et al. 11
Californian winery	2.58			Smyth [28]
Total winery energy use				
South Australian study	2.14			Anon [4]
Italian study		122		Cotana and Cavalaglio [10]
Californian winery	1.62	190.7		Smyth [28]
New Zealand Benchmark	0.47			Van der Zijpp [30]
Canadian study	0.21–1.9			Anon [3]
Australian Benchmark	0.75–2.0			Anon [4]
Australian study			362.5	Anon [5]
Total winery electricity use				
Californian winery	1.09			Smyth [28]
Californian study	0.634			Smyth [28]
Californian study			40–120	Boulton et al. [7]
(Lighting)				
Californian winery		25–35		Smyth [28]
European study		10		Neelis et al. [19]
Canadian study	0.05			Martin [18]
(Refrigeration)				
Californian winery	0.32			Smyth [28]
Italian winery		4.2		Cotana and Cavalaglio [10]
Western Australian winery	0.35			Anon [4]
Californian winery	0.14			Rosenblum [27]
CSWA	0.062			Rosenblum [27]
(Compressed air)				
Californian winery		5		Smyth [28]
(Pumping)				
Wine processes	0.0015			Neelis et al. [19]
Fixed pumping		5		Smyth [28]
Water pumping	0.0038			Galitsky et al. [15]
Cooling activities	0.0058			Neelis et al. [19]
Cleaning activities	0.0167			Neelis et al. [19]
Barrel/bottle cleaning	0.00087			Neelis et al. [19]
Waste water treatment	0.0007			Neelis et al. [19]
Pond aeration	0.016			Neelis et al. [19]
(HVAC)				
Californian winery (mech)	0.144	17		Smyth [28]
Canadian study (H&C)	0.167			Martin [18]
(Fork trucks)				
Californian winery	0.05			Smyth [28]
European study	0.028			Neelis et al. [19]

[a] kWh/l of wine produced, kWh/m^2 of facility floor area and kWh/ton of grapes received

Table 4.4 Wine production processes and associated energy indicators and benchmarks

Process Description	Benchmark metric[a]			Reference
	kWh/l	kWh/m^2	kWh/ton	
(Grape receiving)				
Unloading/processing			5.08	Neelis et al. [19]
Unloading/processing	0.051			Martin [18]
Pressing			10.96	Neelis et al. [19]
(Cooling)				
Total production (white still)	0.158			Karousou et al. [17]
Total production (red still)	0.106			Karousou et al. [17]
Cold treatment (still)	0.021			Karousou et al. [17]
Cold decantation (white still)	0.037			Karousou et al. [17]
(Cold stabilisation)				
Total production	0.029			Karousou et al. [17]
Uninsulated tank	0.317			Dugger [11]
Insulated tank	0.006			Dugger [11]
Flash techniques	0.012			Dugger [11]
(Heating)				
Total production (white still)	0.0467			Karousou et al. [17]
Total production (red still)	0.0757			Karousou et al. [17]
Malolatic ferment (room)	0.067			Neelis et al. [19]
(Bottle fermentation)				
Store cooling	0.0057			Karousou et al. [17]
Store air circulation	0.0019			Neelis et al. [19]
(Wine transfer)				
Western Australian winery	0.0006			Anon [4]
European study	0.0015			Neelis et al. [19]
(Disgorgement)				
Californian winery	0.027			Smyth [28]
Spanish study	0.0083			Karousou et al. [17]
European study	0.0082			Neelis et al. [19]
(Bottling and packaging)				
Californian winery (still)	0.002			Smyth [28]
European study (still)	0.0028			Neelis et al. [19]
Californian winery (spark)	0.03–0.065			Smyth [28]
(Product storage)				
Sparkling	0.006–0.015			Karousou et al. [17]
Barrel aging	0.0057			Neelis et al. [19]
Barrel aging	0.017			Karousou et al. [17]
Still (CSWA)	0.0048			Rosenblum [27]

[a] kWh/l of wine produced, kWh/m^2 of facility floor area and kWh/ton of grapes received

benchmark values, providing a means whereby the winery can analyse their own energy consumption trends and patterns and instigate or follow improvements in energy usage. Tables 4.3, 4.4 and 4.5 detail a range of winery activities with their associated energy indicators and benchmarks extracted from the current literature.

Table 4.5 Washing and cleaning processes and associated energy indicators and benchmarks

Process description	Benchmark metric[a]			Reference
	kWh/l	kWh/m^2	kWh/ton	
(Process hot water)				
Still (Australian)	0.29			Anon [4]
Mixed (California)	0.083			Smyth [28]
Still (California)	0.18			Rosenblum [27]
Still (CSWA)	0.102			Rosenblum [27]
(Bottles)				
Still (Spanish)	0.037			Karousou et al. [17]
(Tanks and barrels)				
Sparkling (Spanish)	0.0936			Karousou et al. [17]
Still (Spanish)	0.0097			Karousou et al. [17]
Still (California)	0.077			Rosenblum [27]
Still (CSWA)	0.041			Rosenblum [27]
(Line sterilisation)				
Still (California)	0.00315			Rosenblum [27]
Still (CSWA)	0.0027			Rosenblum [27]
(House keeping)				
Still (California)	0.00315			Rosenblum [27]
Still (CSWA)	0.0027			Rosenblum [27]
(Domestic hot water)				
Mixed (California)		3.1		Smyth [28]

[a] kWh/l of wine produced, kWh/m^2 of facility floor area and kWh/ton of grapes received

The previous tables present a range of benchmark indicators from individual wineries to collective groupings to regional/national benchmark standards. What is apparent is that the individual values differ depending upon many variables; location, region, winery age, wine type and quality, facility size and production output. This spread implies that one set of benchmarks cannot be universally applied, but rather each wine producing region should have a locally produced set of standards. In addition, a range of benchmarks is necessary to cover the main differences in processes within. That said, taking a 'broad brush' approach, all commercial 'western' wineries, if operating efficiently should be using less than 1.5 kWh/l of wine produced, with 2.5 kWh/l seen to be an upper limit.

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Chapter 5
Review of Existing Solar Wineries

5.1 Introduction

This chapter is a review of the various wineries worldwide that have installed an active solar collection system that can effectively utilise the collected energy to offset a significant proportion of the winery's energy requirement. The review catalogues the size, range and description of the many various systems installed globally and provides a detailed collection of case studies to give the reader an indicative representation of the type of solar installations currently being used in winemaking facilities throughout the wine producing regions of the world.

Globally, there are an estimated 184,300 [1] winemaking facilities that could economically utilise solar energy. Of this total to date only 293 have been identified has having a substantial active solar installation, all of (except one) which reside in the traditional 'Western' nations, commonly associated with quality wine production. However, this value is not exclusive; there are many more wineries that may be added to the list. In the compilation of this database finding relevant information regarding wineries with a solar installation has been a difficult and time consuming process. For many reasons, be it issues of privacy, cost or access, a winery may choose not to publicly advertise their installation. Furthermore, many wineries are excluded from the list as they operate with passive design only or the system installed is too small to represent a significant contribution to the winery's operation (domestic sized installations have been excluded).

5.2 Wineries of the World

The size of individual vineyards in the world is different. In the old world, Europe's 2.4 million wine producers are an average of 1.5 ha each, while the average new world vineyard is 50 ha, providing considerable economies of

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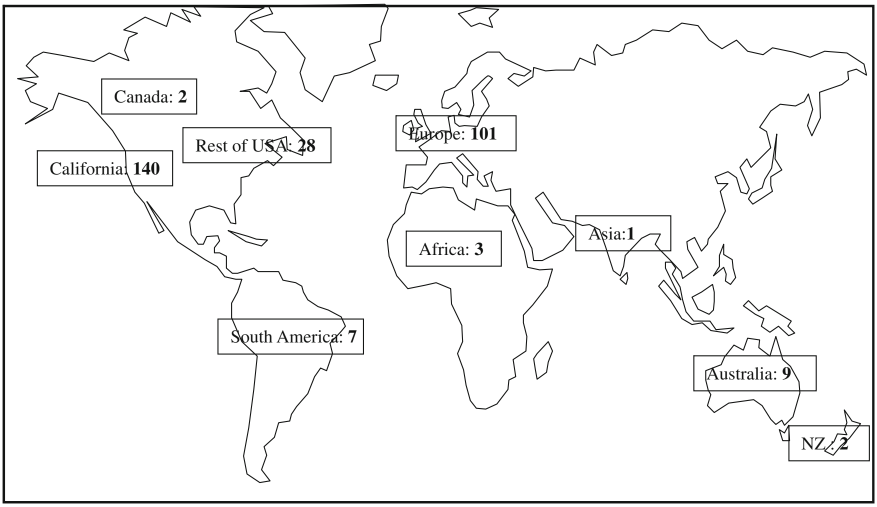


Fig. 5.1 Global distribution of active solar wineries

scale [2]. The EU represents almost 50% of the world's vineyard coverage, with almost 3.6 million ha, whilst the recognised new world producers cover almost 1.2 million ha in just over 23,500 vineyards. However, the bulk of the vineyards in the old world are owned by 'small farms' and holdings growing grapes for wine production are in general small. More than 71% have less than 5 ha, while more than 12% range from 5 to 10 ha, leaving 17% as 'larger, commercially viable' vineyards [1].

If we combine the recognised new and old world winegrowers, representing the most developed wine producing nations, there is an estimated 184,300 (new world, 23,500 + Europe, 160,800 [1] establishments that could economically utilise solar energy (based on regions with up-to-date viticultural and oenological techniques). Of this number very few are actually making use of this resource. Figure 5.1 illustrates the global distribution of active solar wineries detailed by [10]. This database of international solar wineries was compiled from personal site visits, email correspondence, communication with solar installation contractors and winery web sites. Whilst this list identifies the range and spread of systems worldwide, it is not exclusive and it is recognised that more wineries remain to be catalogued.

A large proportion of solar wineries are located in either California or Germany, combined they represent nearly 2/3 of all wineries currently 'identified', with 48% and 16%, respectively. This inevitably leads one to ask, why does California and Germany have such a high proportion of the known solar wineries in the world, particularly when their respective winery characteristics and wine production processes (and solar system designs) are so different. The answer to this question is simply…. 'economics'. All of the traditional wine producing regions have a solar resource that can yield significant returns in energy collection, yet only in

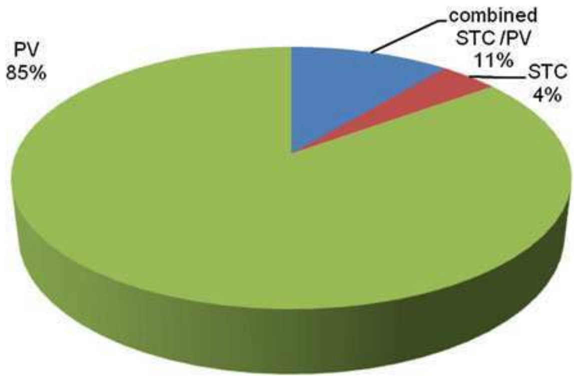


Fig. 5.2 Types of solar installation in European wineries

California has there been a substantial upfront financial package to entice wine producers into committing to a solar installation. Similarly, Germany has had a long established feed in tariff that makes the installation of a solar installation viable economically. In both these regions, the available economic incentives have enticed a large number of wine producers to consider solar as a viable energy solution. In many of the world's other wine producing regions similar payment based financial options do exist but they tend to be less lucrative or not as widely available and thus wineries may still have to make a significant capital investment. Broadly speaking, it is too narrow to only consider financial reasons, there are many other contributing factors, such as winery size and operation, level of modernity, utility access, structural, historical and aesthetic constraints that need to be considered and it is therefore appropriate that this topic is discussed in greater detail in the following Chap. 6.

5.2.1 Old World

Given the vast number of wineries that exist in the old world wine producing regions, relatively few have adopted any form of solar renewables, although there are some notable exceptions. Table 5.1 lists some of the solar wineries to be found in the old world (Europe) that have been catalogued to date, together with some important system details.

Of the 101 identified solar wineries in the recognised old world, Photovoltaic (PV) installations make up the biggest share of the market, with 85%. Combined PV and solar thermal represent 11% and solar thermal only is 4% (Fig. 5.2).

Concentrating on solar PV installations, Germany has almost as many solar winery installations as the rest of Europe combined (at 45%), with Italy, France and Spain being next with 25, 11 and 8%, respectively. This is broadly in-line with the general statistics for solar installations in the European market. From the annual Photovoltaic status report (2009) from the European commission's joint

Table 5.1 Details of all the known solar wineries currently operating in Europe

Europe			
Winery name	Region	Size	Details
Winery Cobenzl	Vienna, Austria	PV—41.76 kWp DC STC—18 m^2	232 roof mounted modules covering an area of 304 m^2 are connected to seven inverters. There also is a solar thermal system supplying 9,500 kWh/year for winery water heating
Weingut Kollwentz	Burgunland, Austria	PV—not available	
Peitler winery	Leutschach, Styria, Austria	STC—100.8 m^2	Combined solar thermal and biomass systems installed in the winery. Flat plate collectors mounted on roof
Weingut Triebaumer	Rust, Austria	PV—10 kWp DC, yielding 11,500 kWh/year	Roof mounted installation
Winery Umathum	Burgenland, Austria	PV—20 kWp DC	93 roof mounted (220 W) modules covering 150 m^2 at 45%, facing southeast
Adissan winery	Languedoc-Roussillon, France	PV—200 m^2	Roof mounted installation
Winery 'Cave de Bonnieux'	Rhone, France	PV—Awaiting installation	
Champagne Drappier	Urville, Champagne, France	PV—not available	Building a new solar-powered winery
Le Cellier des Templiers (winemaking co-operative)	Banyuls, France	STC—134 m^2	Roof mounted evacuated tube collectors supplying thermal energy to a 52 kW adsorption refrigeration system to AC the cellar

(continued)

Table 5.1 (continued)

Europe

Winery name	Region	Size	Details
Château Clerc Milon	Bordeaux, France	PV—300 m^2	
Saint Chaptes (winemaking co-operative)	Nîmes, France	PV—161 kWp DC, yielding 179,627 kWh/year, covering 1,150 m^2	700 roof mounted Tenesol 2,200 230 Wp modules connected to 22 SMA inverters
Chateau Montrose	Bordeaux, France	PV—1,000 m^2	Roof mounted installation
Coneilla-of-the-Riviière	Languedoc-Roussillon, France	PV—yielding 36,000 kWh/year, covering 210 m^2	Roof mounted installation that will cover the demand for energy of the cellar and the production of wine
Domaine Sainte Rose	Languedoc-Roussillon, France	PV—not available	
Duval-Leroy winery	Champagne, France	PV—29 kWp DC covering 250 m^2	180 ALEO S_73 façade BIPV modules
Vinipolis winery	Florensac, Languedoc, France	PV—not available	Roof integrated and carport
Achaia Clauss Winery	Patras, Greece	PV—20 kWp DC	Solar water heating system with 10 m^3 storage, installed on the winery roof
Weingut Besenwirtschaft	Brackenheim, Germany	PV—229.52 kWp DC	1208 flush roof mounted UP Solar UP-M190 M modules connected to 8 RefuSol 20 kW and 4 RefuSol 13 kW inverters
Weingut Deppisch	Erlenbach, Germany	PV—250 m^2	
Durbach vineyard	Baden-württemberg, Germany	STC—7 modules PV—90 modules	Flush roof mounted installation
Weingut Duttenhofer	Edesheim, Germany	PV—approximately 16 kWp DC	98 roof mounted modules
Weingut Eugen Bender	Eschbach, Pfalz, Germany	PV—approximately 10 kWp DC	57 flush roof mounted modules
Winery Faschian	Hessigheim, Germany	PV—30 kWp DC	Roof mounted installation
Weingut Fritz Klein	Niederhorbach, Germany	PV—approximately 23 kWp DC	136 tilted and flush mounted roof modules

(continued)

Table 5.1 (continued)

Europe			
Winery name	Region	Size	Details
Weingut Fünfschilling	Baden-Württemberg, Germany	PV—103 kWp DC	572 roof mounted suntech modules STP180S-24AC
Gretzmeier winery	Merdingen, Germany	PV—15.84 kWp DC, covering an area of 120 m^2, yielding 15,000 kWh/year	96 roof mounted (165 W) modules
Weingut Haag	Uissigheim, Germany	PV—38.7 kWp DC	Roof mounted installation
Hall winery	Freiburg-Opfingen, Germany	PV—26.52 kWp DC	160 roof mounted Schott Solar ASE-165-GT-FT/MC modules connected to SMA SMC 8,000 TL inverters
Weingut Hessigheim	Hessigheim, Germany	PV—36 kWp DC	400 roof mounted Phoenix Solar modules connected 2 Fronius IG Plus 100 and 2 Fronius IG Plus 70
Winegrowing estate Heupel	Buggingen-Betberg, Germany	PV—14.11 kWp DC	Roof mounted Suntech modules and SMA inverters
Winery Hitziger	Bad Bergzabern, Germany	PV—18 kWp DC	
Winery Hague	Uissigheim, Germany	PV—28.7 kWp DC	Roof mounted installation in two arrays following (1 flush the other fin)
Winery Hug and 'The Old Cooperage'	Pfaffenweiler, Freiburg, Germany	PV—27.54 kWp DC	167 roof mounted Schott Solar ASE-165-GT-FT/MC connected to SMA inverters
Weingut Ihringen	Ihringen, Germany	PV—19.04 kWp DC	112 MF 170 EB4 roof (fin at 28°) mounted modules connected to a Fronius IG 40 inverter

(continued)

Table 5.1 (continued)

Europe

Winery name	Region	Size	Details
Weingut Kauffer	Niederhorbach, Germany	PV—8 kWp DC	50 flush mounted roof modules
Weingut Karlheinz Roth	Roschbach, Germany	PV—not available	Roof mounted modules
Winery Kiessling	Heilbronn, Germany	PV—53.64 kWp DC	298 roof mounted Schüco SPV 180-SMC1 modules in six arrays connected to SMA inverters
Weingut Kitzer	Badenheim/Rheinhessen, Germany	PV—50 kWp DC, yielding 43,563 kWh/year	264 Solon (155 W) roof mounted modules covering an area of 406 m^2 connected to Sunny Boy SB 5,000 inverters
Weingut Köbelin	Eichstetten, Baden, Germany	PV—34.65 kWp DC	210 roof mounted Schott ASE-165-GT-FT/MC modules connected to SMA SMC 8,000 TL inverters
Weingut Landau	Landau, Germany	PV—125.55 kWp DC	1674 First Solar FS 75 W roof mounted modules connected to SMA inverters
Vineyard Maeurer	Dackenheim, Germany	PV—39.6 kWp DC, covering an area 310 m^2, yielding 37,620 kWh/year	240 roof (fin) mounted Suntech (165 W) modules connected to six SMA Sunny Boy 5000A inverters
Weingut Merkel	Kleinniedesheim, Germany	PV—8.28 kWp DC	Roof mounted installation
Weingut Merk	Ellerstadt, Germany	PV—not available	Various arrays of roof mounted thin film modules
Winery Mesel	Bad Dürkheim, Germany	PV—16 kWp DC	Roof mounted installation
Weingut mueller	Ellenz/Mosel, Germany	PV—8.32 kWp DC, covering an area of 70 m^2	32 roof mounted modules

(continued)

Table 5.1 (continued)

Europe			
Winery name	Region	Size	Details
Weingut Nopper	Buchholz, Germany	PV—20.6 kWp DC	Tilted roof mounted modules
Öko-Weingut	Pfaffenheim, Germany	PV—12.2 kWp DC, yielding 11,000 kWh/year covering an area of 95 m^2.	55 tilted roof mounted monocrystaline IBC Solar modules
Weingut Opfingen	Freiburg-Opfingen, Germany	PV—30 kWp DC,	182 Suntech roof (fin) mounted modules arranged over five roofs
Weingut Petershof	Gertrudenhof, Impflingen, Germany	PV—30 kWp DC	Roof mounted system on winery barn
Weingut Pioth	Roschbach, Germany	PV—not available	Mixture of tilted and flush mounted roof modules and evacuated STC
Weingut Pfaffmann	Gertrudenhof, Impflingen, Germany	PV—317 kWp DC, covering an area of approximately 3,500 m^2, yielding 291,640 kWh/year	4,227 First Solar (75 W) roof mounted modules connected to 45 inverters (Solamax and Fronius)
Winery Sauer	Nussdorf–Landau, Germany	PV—35 kWp DC,	Roof mounted installation
Weingut Schneider	Ellerstadt, Germany	PV—90.585 kWp DC	
Weingut Schloss	Ortenberg, Germany	PV—40 kWp DC	
Weingut Schloss	Salenegg, Germany	STC—70 m^2	Solar thermal collectors with 3,200 l storage to supply DHW and winery process hot water in addition to a 15 kW absorption system supplying 4.4 kW cooling

(continued)

Table 5.1 (continued)

Europe

Winery name	Region	Size	Details
Weingut Shepherd	Neustadt/Pfalz, Germany	PV—40 kWp DC	Roof mounted installation
Weingut Spreitzer	Rheingau, Germany	PV—27 kWp DC	
Weingut St. Michaelshof	Worms, Germany	PV—76 kWp DC	Roof mounted Yingli modules connected to SMA SMC inverter
Weingut Trautwein	Lonsheim, Pfalz, Germany	PV—143.5 kWp DC, yielding 136,155 kWh/year	798 Lieferant HB (180 W) roof mounted modules connected one REFU 100 kW inverter
Winery Veddeler	Erpolzheim/Pfalz, Germany	PV—30 kWp DC, covering an area of 230 m^2, yielding 26,138 kWh/year	140 Solon (215 W) roof mounted modules connected to five Solarmax 5,000 inverters
Weingut Wirth	Wollstein, Germany	PV—42.66 kWp DC, yielding 38,350 kWh/year	237 roof mounted Yingli Solar YL 180 W modules connected to three SMA Solar Technology SMC 10,000 TL, 1 SMA Solar Technology SB 5,000 TL and 1 SMA Solar Technology SB 3,800 ESS inverters
Weingut Wirth	Rheinhessen-Pfalz, Germany	PV—29.07 kWp DC	92 alfasolar Pyramid 80-316 W roof mounted modules connected to two 15 kW SMA inverters
Weingut-Wolfahrt,	Astheim, Germany	PV—8.23 kWp DC	36 flush roof mounted modules connected to two solar world inverters

(continued)

Table 5.1 (continued)

Europe			
Winery name	Region	Size	Details
Alois Lageder	Bolzano, Italy	STC—24 m^2 PV—37.3 kWp DC, yielding 38,000 kWh/year covering 255 m^2	Fixed solar thermal flat plate collectors and 316 Solar Fabrik modules mounted on a shading structure at 30° facing south-southeast, connected to various SMA Sunny Boy inverters. (with another 10 kWp DC being installed)
Agriturismo San Mattia	Veneto, Italy	PV—not available STC—small	52 roof mounted modules with roof integrated solar thermal collectors
Barlo vineyard	Asti, Italy	PV—700 kWp DC	CSI modules
Cantine Giuseppe Olivi	Siena, Tuscany, Italy	PV—not available	Mounted on roof of winery
Castello Fageto winery	Pedaso, Italy	PV—not available	Winery is energy independent thanks to solar power
CAVIT	Trentino, Italy	PV—not available	Roof mounted installation
Collavini winery	Udine, Italy	PV—72 kWp DC, yielding 79,200 kWh/year, covering 400 m^2	240 roof mounted Sunpower SPR-300-WHT-I modules connected to 6 Sunpower SPR 12000F inverters
Corvezzo	Cessalto, Veneto, Italy	PV—198.54 kWp DC,	1036 Aleo 155 W modules + 156 Aleo 150 W modules + 104 Aleo 140 W modules connected to 24 SMA SMC 8000TL inverters

(continued)

Table 5.1 (continued)

Europe			
Winery name	Region	Size	Details
Cortemilia winery	Southern Piedmont, Italy	PV—19.78 kWp DC, yielding 24,546 kWh/year	86 roof mounted Sanyo HIP-230HDE1 modules in 5/2 Strings covering 120 m^2 connected to 4 x SolarMax 6000S inverters
Donnafugata	Sicily, Italy	PV—18 kWp DC, yielding 28,000 kWh/year	Roof mounted system. One of the first wineries in Italy to use PV. Approximately 30% solar fraction.
Ermacora	Friuli, Italy	PV—72.9 kWp DC, covering 542.7 m^2	324 ALEO S18.225 (225 W) roof mounted modules
Feudo Arancio (Mezzacorona Group)	Sicily, Italy	PV—44.9 kWp DC STC—flat plate collectors	264 roof mounted (integrated) Mitsubishi (170 W) modules 16 roof mounted flat plate collectors mounted at 30° tilt to provide extremely high water temperatures for the cleaning and sterilization of the winery
Forteto della Luja	Piemonte, Italy	PV—not available	Roof mounted modules
Martinenga winery (Marchesi di Grésy)	Barbaresco, Italy	PV—50 kWp DC, yielding 54,000 kWh/year	228 REC 220A modules installed in a carport shading structure
Monte Vibiano	Umbria, Italy	PV—not available	Free standing vehicle charging doc

(continued)

Table 5.1 (continued)

Europe

Winery name	Region	Size	Details
Nosio (*Mezzacorona Group*)	Mezzacorona, Italy	PV—382.2 kWp DC, predicted to yield 400,000 kWh/year, covering an area of 4,460 m^2 STC—560 m^2	5,104 First Solar roof mounted thin film (75 W) modules connected to two Aurora 200 kW inverters 210 flush mounted roof flat plate collectors on the new facility to provide hot water used in the bottling process
Planeta	Sicily, Italy	PV—covering 300 m^2	
Rizzi cellar	Piedmont, Italy	PV—19.8 kWp DC, yielding 25,000 kWh/year, covering 149.7 m^2	117 roof mounted modules (170 Wp) at 35°, south facing
Rubbia al Colle	Tuscany, Italy	PV—100.64 kWp DC, yielding 121,032 kWh/year, covering 1,200 m^2	544 ground mounted SP System SPS 185P modules connected to two SIEL SPA model Soleil 50 inverters
Sandrone (Barolo) winery	Cuneo, Italy	PV—19.58 kWp DC, 110 m^2, yielding 25,000 kWh/year	Roof mounted 87 SPR-225-WHT modules
Tenuta Vitanza winery	Veneto, Italy	PV—20 kWp DC	Roof mounted modules
Tenuta San Vito	Montelupo, Tuscany, Italy	STC—not available	Hot water supplemented with solar modules
Tenuta Santomè	Treviso, Italy	PV—198.44 kWp DC, yielding 196,400 kWh/year	888 flush roof mounted Polysilicon ECHO REC 225PE (225 W) modules connected to 7 Fronius (IG500, IG400, IGPLUS 120, IGPLUS100) inverters

(continued)

Table 5.1 (continued)

Europe			
Winery name	Region	Size	Details
Torresella winery	Veneto, Italy	PV—not available	Winery installation
Villa Abius (Mezzacorona Group)	Sicily, Italy	PV—48.9 kWp DC tracking yielding 104,000 kWh/year and 152 kWp DC fixed	288 ground mounted double axis tracking (one manual, one automated) Mitsubishi (170 W) modules 800 fixed ground mounted Mitsubishi (190 W) modules connected to a 50 kW and 100 kW Aurora inverters
Carmey Avdat winery	Negev desert, Israel	PV—50 kWp DC	Roof mounted system providing 65% of the winery's electricity. Israel's first solar powered wine producer
Dalton winery	Upper Galilee, Israel	PV—100 kWp DC	Sunpower modules. The largest PV installation to date in Israel.
Cortes de Cima	Alentejo, Portugal	STC—56 m^2 rated at 45 kW PV—7.9 kWp DC, covering 2 × 30 m^2, yielding 14,400 kWh/year	48 flat plate collectors with 5,000 l storage. Two double axis trackers each with 22 polycrystalline silicon (180 W) modules providing 16% of the winery annual electric consumption. The first solar winery in Portugal
Cumbres de Abona	Tenerife, Spain	PV—52.94 kWp DC, yielding 79,198 kWh/year	306 roof mounted ST 173 F modules
Bodega Emina	Valladolid, Spain	PV—100 kWp DC	560 roof mounted BP 185 W modules

(continued)

Table 5.1 (continued)

Europe			
Winery name	Region	Size	Details
Bodegas Portia (Faustino Group)	Ribera del Duero, Spain	PV—not available	New winery with roof integrated PV installation
Finca La Estacada winery	Levante, La Mancha, Spain	PV—100.8 kWp DC	504 Ersol Ganymed 200P modules connected to 18 SMA SMC 5000A inverters mounted on aluminium mounting structures
Viñedos del Ternero	Miranda de Ebro, Rioja Alta, Spain	PV—49.2 kWp DC, yielding 64,000 kWh/year STC—not available	Roof mounted PV installation with solar thermal system
Torres vineyard	Vilafranca del Penedes, Catalonia, Spain	PV—673.92 kWp DC, 12,000 m^2, yielding 900,000 kWh/year STC—100 m^2	2592 SunTech (260 W) tilted roof mounted modules connected to two 350 W Siemens Solar inverters produces 11% of the winery's electrical need. An additional double axis tracking PV supplied power to the lighting installation of the bodega. 100 m^2 of roof mounted (tilt) flat plate collectors supplies 50% of the hot water needs of their bottling plant
La Bodega Cooperativa Santa Catalina	Alicante, Spain	PV—121.38 kWp DC, 1,000 m^2, yielding 194,208 kWh/year	714 roof mounted modules offsetting 13% of the winery's electricity/year
Weingut Batardon	Geneva, Switzerland	PV—10 kWp DC	Flush roof mounted GE modules
Hattingley Valley	Hampshire, UK	PV—28.86 kWp DC, yielding 24,791 kWh/year	156 flush roof mounted AS5M-185 modules

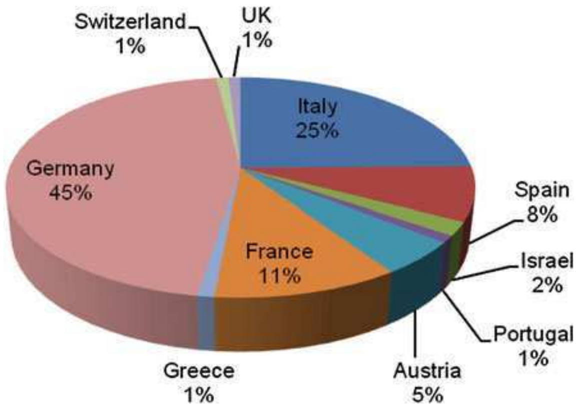


Fig. 5.3 Distribution of European solar wineries by country

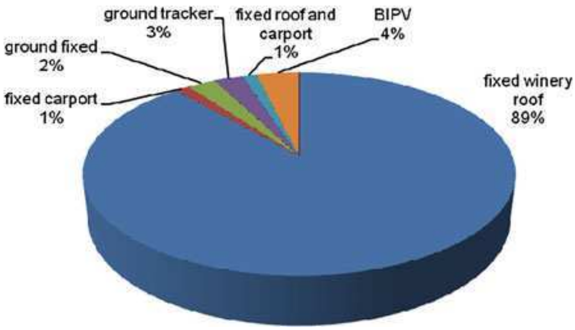


Fig. 5.4 Mode of PV installation mounting for Europe

research centre (JCR) Germany had a cumulative PV capacity of 9,800 MWp, Spain had 3,500 MWp, Italy had 1,200 MWp, the Czech Republic had 460 MWp and Belgium had 360 MWp [7]. Nationally, France does not have a significant accumulated solar PV tally but given the total number of French vineyards/wineries that exist, even a small percentage uptake in solar can result in a significant value in global terms (Fig. 5.3).

Of the European solar wineries investigated (Fig. 5.4), nearly all utilised fixed, roof mounted installations (both tilted and flush) and only a few Italian and Portuguese wineries utilised a ground mounted systems (fixed and tracking).

As previously mentioned, this database is not exclusive. This is particularly prevalent to European wineries and more specifically to Germany. A substantial feed in tariff incentive has existed in Germany for many years and many winemaking establishments have taken advantage of this financial offer and installed a solar system. So it is fair to say that of the 46 German solar wineries identified to date, the true value is probably significantly larger. However, there are still a greater number of wineries that have not installed a solar system. Many of the German wineries are small, traditional family operated wineries, handed down from generation to generation and many are located in little compact 'wine hamlets and villages', often still producing wine from old historical buildings.

Fig. 5.5 A 'Weinstrasse' in a typical small wine village in Germany, containing several small family operated wineries

Figure 5.5 shows a 'Weinstrasse' running through the small wine village of Forst, Pfalz in Germany, where many small family run wineries still operate. In this example, due to the historical relevance and rustic beauty of the buildings, the local authority bans the installation of solar systems. This local legislation is not restricted to Germany but is also prevalent in many other EU countries. In Umbria in Italy, for example, some local authorities apply restrictions on historical buildings so strictly that practically no one can install a solar system.

In many of these 'Weinstrasse' examples, whether it is due to historical relevance, lack of space to expand, issues relating to access or shading, condition of the old building structure or lack of finance, solar installations are non-existent or small. Furthermore, these wine communities can be influenced by the dominant wine family (and their particular preference) and it is not unusual to observe many solar wineries in one village whilst a village just down the road may have none at all.

During the compilation of the database, a significant number of European wineries with a small solar installation were excluded. Figure 5.6 gives an illustration of a small winery in the Pfalz region of Germany that has invested in solar but due to some of the reasons mentioned previously, it has not been classified as substantial and has therefore not been included in the database. In this example, whilst a solar PV installation is clearly visible, there are only 18 modules, giving approximately 3 kWp. This installation, given the scale of systems elsewhere and the demand for energy within the winery, is too small to make a significant contribution. In addition, some village wineries, given the potential economic returns, have built basic structures on their vineyard land to house equipment or provide additional storage but are primarily used to mount a PV installation. These PV installations are also excluded as they do not feed into the winery supply but rather directly into the supply authority grid and therefore cannot be described under the term 'solar winery' as defined in this text.

Of course, lack of available mounting space (both winery and vineyard) has not been a barrier to some wineries and in the small community of Kappelrodeck,

Fig. 5.6 A winery in the Pfalz region of Germany with a small PV installation

Germany, a winery rented public roof space for its solar installation. Weingut König in the district of Steinebach had no suitable roof space for PVs so the winery took advantage of an offer to install the system on the roof of the local fire station. So far the system has yielded almost 30,000 kWh/year in electricity for the winery. Although this is technically not a solar winery (it is not within the winery or vineyard site), it offers a methodology whereby solar energy can be captured and utilised directly. In another interesting development concerning solar and the winemaking industry, a former winery, Erlasse winery estate in Franken, Bavaria has been converted into a 12 MWp solar power plant, consisting of 16,896 modules mounted in 1,480 Solon Mover arrays.

Some interesting observations are apparent when we look at the German installations. Nearly all the installations are roof mounted. This is in part due to greater incentives to mount on buildings which are aimed at protecting valuable agricultural land. In fact, incentives for ground mounted PVs expired from the 1st January 2011.

A significant proportion of the PV installations are less than 30 kWp and an even greater percentage are less than 60 kWp. The local German power supply companies are required by law to pay for interconnection costs for any PV installation no greater than 30 kWp. Many wineries have therefore opted to keep installation costs low by installing a smaller system. However, the winery may also install a second system, again not more than 30 kWp, equating to a total that does not exceed 60 kWp and again the power supply company will pay for the interconnection.

Overall this is apparent from the database and of the 73 wineries with complete system information, 47% are less than or equal to 30 kWp, 70% are less than 60 kWp and only 19% are greater than 100 kWp. When we look at German wineries only, the interconnection restrictions are very evident, with 57.5% less than or equal to 30 kWp, 82.5% below or equal to 60 kWp and less than 12.5% greater than 100 kWp. Italian and Spanish installations tended to be significantly bigger compared to German installations with the average system size calculated as 135 kWp and 183 kWp against 48.6 kWp, respectively.

5.2.2 New World

The new world, whether due to its larger vineyards or modern winemaking approach has been more open to the concept of adopting large scale solar renewables with photovoltaic systems being by far the most popular, although solar thermal systems are common and a few wineries have installed both. California, in particular, seems to be particularly advanced in the integration of solar installations, centred on the world renowned regions of the Napa Valley and Sonoma County.

5.2.2.1 Wineries Using Solar Energy in USA

As of November 2008, the number of wineries in the USA was 6,101 [9] and within the USA, the states with the most wineries are as follows:

- California with 3,005 total wineries (2,219 bonded, 786 virtual)
- Washington with 539 (511 bonded, 28 virtual)
- Oregon with 398 (321 bonded, 77 virtual)
- New York with 246 (232 bonded, 14 virtual)
- Texas (160)
- Virginia (152)
- Pennsylvania (136)
- Ohio (109)
- Michigan (106)

California has just over 49% of all wineries registered in the USA (bonded and virtual) and when it comes to solar wineries, California also has the largest share.

California

California is by far the largest wine producing area in the USA. California comprises of six main American viticultural areas (AVAs); Central Coast and Santa Cruz Mountains, Central Valley, Klamath Mountains, North Coast, Sierra Foothills and South Coast of which there are many more sub-AVA regions. There are a total of 140 solar wineries currently operating in California, the majority of which are located in the quality wine producing regions close to the coast and north of the Bay Area. Although California has a total of 3,005 wineries, only 2,219 are bonded, therefore ignoring virtual wineries, only 6.3% of Californian wineries have adopted active solar, but this value is much greater in the quality wine producing regions. In a study of the leading quality wine producing regions of California [4], both Napa and Sonoma counties were leading the way in solar uptake. In 2008 in Napa County there were 391 bonded wineries of which 43 had installed some form of substantial solar system, representing 11.0%. In Sonoma

County there were 260 bonded wineries of which 20 had installed some form of substantial solar system, representing 7.7%. San Luis Obispo has 109 bonded wineries of which 7 had installed some form of substantial solar system, representing 6.4%. In Mendocino County there were 56 bonded wineries of which 4 had installed some form of substantial solar system, representing 7.1%. There have been a number of further installations since that date. Table 5.2 lists all the known solar wineries currently operating in the state of California, giving size and system details.

The overwhelming majority of solar winery installations in California are PV, with only a few wineries opting for solar thermal only or in combination with PV (Fig. 5.7). In contrast to the old world, given the availability of land, there is also a greater mix in the types and forms of installation mode utilised.

Figures 5.8, 5.9 and 5.10 illustrate the breakdown in the various forms of PV mounting formats utilised in the various regions in California.

Considering the combined breakdown of PV installation formats within California (Fig. 5.11), 57% are roof mounted and 28% ground mounted with the remainder being a mixture of different mounting solutions or differing mounting combinations. This clearly demonstrates the diversity of mounting arrangements available to the winery, a fact that is also borne out by range of manufacturers used in the installations.

By installed module type (not bulk quantity), Sharp modules are the most popular at 27%, followed by SunPower, Sanyo and Kyocera as shown in Fig. 5.12. SMA SunnyBoy and Xantrex inverters are the most popular installed inverter by type with 38% and 27%, respectively (Fig. 5.13).

The average size of a Californian winery installation is 169.1 kWp with no significant difference observed between the various winegrowing regions. Comparing the size distribution of the 120 wineries with complete system information, 28.3% are less than or equal to 30 kWp, 55% are less than 60 kWp and 35% are greater than 100 kWp, with 5 winemaking facilities greater than 1 MWp.

Other States

By default, if California represents 49% of the country's wineries, then 51% reside in the rest of the USA. Of this percentage, Washington, Oregon and New York are the most significant, with 9, 6.5 and 4%, respectively. This again is evidenced by the share of solar wineries, with these three states representing the bulk of solar wineries in existence, although Oregon seems to have a greater share in solar wineries as per its total number of wineries, as does Pennsylvania. As detailed in Table 5.3, there are 28 solar wineries in the rest of the USA, of which 13 are in Oregon, 3 in Pennsylvania, 4 in New York, and 1 each in Washington, Connecticut, North Carolina, Georgia, Tennessee, Montana, Virginia and Idaho. Only Oregon and Pennsylvania have a significant percentage of solar wineries to bonded wineries, 4.1 and 2.2%, respectively.

Table 5.2 Details of all the known solar wineries currently operating in the state of California

California			
Winery name	Region	Size	Details
Central Coast			
Alban vineyards	San Luis Obispo, Central Coast	PV—55 kWp DC, yielding 88,000 kWh/year	Ground mounted installation, offsetting 78% of the total electrical usage
Casa Barranca	Santa Barbara, Central Coast	PV—not available	Roof mounted PV installation
Concannon vineyard	Livermore Valley, Central Coast	PV—150 kWp DC	Flush roof mounted
Fenestra winery	Livermore Valley, Central Coast	PV—19 kWp DC	96 flush roof mounted modules
Foxen winery	Santa Barbara, Central Coast	PV—yielding, 60,000 kWh/year	180 REC roof mounted modules providing 70% of Foxen's electricity
Gonzales winery, constellation wines.	Monterey, Central Coast	PV—1,176 kWp DC, yielding 1,700,000 kWh/year, covering 15,800 m^2.	6,358 Mitsubishi 185 W modules mounted on the main winery warehouse roof connected to two inverters, supplying 60% of the winery's electricity
Tolosa winery	San Luis Obispo, Central Coast	PV—390 kWp DC	2,508 modules in a ground mounted tracking system, covering three acres
Central Valley			
Bokisch vineyards	Lodi, Central Valley	PV—22.5 kWp DC	Mounted at a 22° incline, the system supplies electricity for two irrigation pumps, the main shop and two homes

(continued)

Table 5.2 (continued)

California

Winery name	Region	Size	Details
Castle Rock vineyards	Delano, Central Valley	PV—1,130 kWp DC, yielding 1,700,000 kWh/year	5,400 roof mounted Kyocera 210 W modules to provide approximately 69% of the power requirements for the winery cold storage facility
Fitzpatrick winery	Fair Play, Central Valley	PV—40 (30 + 10) kWp DC	2 PV installations. A 30 kWp roof mounted system comprising 220 modules and five double tracking system units each with 16 modules
Green Hills winery sent email	Lodi, Central Valley	PV—not available	Ground mounted system
LangeTwins winery and vineyards	Lodi, Central Valley	PV—250 kWp DC	Combination of fixed roof and ground mounted systems
Lucas winery	Lodi, Central Valley	PV—17.5 kWp DC, covering an area of 160 m^2	160 south facing, roof mounted modules on the roof of the converted barn
Milla vineyards	Fresno, Central valley	PV—11.2 kWp DC, yielding 17,800 kWh/year	66 ground mounted Mitsubishi 170 W modules located close to the winery
Naggiar vineyards and winery	Nevada County, Central valley	PV—25 kWp DC	Flush mounted roof installation on the south side of the winery
New Clairvaux vineyard	Tehama County, Central Valley	PV—59.4 kWp DC, yielding 84,460 kWh/year	Cistercian-Trappist monastery with a fixed ground mount system providing 57% of the Abbey's annual electricity

(continued)

Table 5.2 (continued)

California			
Winery name	Region	Size	Details
Shenandoah vineyards	Plymouth, Central valley	PV—63 kWp DC	Tilted roof mounted installation supplying 100% of the winery's need
UC Davis educational winery	Davis, Central Valley	PV—102 kWp DC	442 flush roof mounted CS6P-230 modules supplying 100% of the winery's need
Van Ruiten winery	Lodi, Central Valley	PV—49.8 kWp DC, yielding 69,700 kWh/year	224 Sharp 216 W modules mounted at an incline on the winery roof connected to six SMA 7000 US and one SMA 6000 US inverters, supplying 50% of the winery's electricity
Napa County			
Amizetta vineyards	Howell Mountain, Napa County	PV—27.7 kWp DC	PV installation mounted on the winery roof, supplying 90% of the power needed for the residence and winery
Araujo estate	Calistoga, Napa County	PV—60 kWp DC	Fixed ground mounted array located on the hill behind the winery
Ballentine vineyards	St Helena, Napa County	PV—87 kWp DC 76 kWp AC, yielding 114,169 kWh/year	512 Mitsubishi 170 W roof mounted modules connected to one 75 kW Satcon inverter
Beringer (Treasury)	St Helena, Napa County	PV—1,340 kWp DC, yielding 1,860,245 kWh/year	Flush roof mounted system is the largest solar installation at a winery in the USA
Boeschen vineyards	St Helena, Napa County	PV—30 kWp DC	Sanyo modules

(continued)

Table 5.2 (continued)

California

Winery name	Region	Size	Details
CADE winery	Howell Mountain, Napa County	PV—30 kWp DC	175 roof mounted Sanyo HIP-190BA3 modules connected to a SMA America inverter. The system covers 40% of the winery's angled roof
Casa Nuestra	St Helena, Napa County	PV—19 kWp DC	Nearly 150 modules tilt ground mounted
Chappellet	Chiles Valley, Napa County	PV—202 kWp DC, yielding 240,744 kWh/year, covering 1,860 m^2	960 modules, self ballasted ground mounted at a tilt of 15° facing 180° south
Chateau Montelena	Calistoga, Napa County	PV—220 kWp DC	Ground mounted system. Solar installation supplies 100% of the winery's power
Cimarossa	Howell Mountain, Napa County	PV—not available	
Cuvaison estates	Carneros, Napa County	PV—249.9 kWp DC, yielding 294,417 kWh/year	1428 SunTech Power roof mounted modules connected to a 225 kW Xantrex PV225 inverter
Domaine Carneros	Carneros, Napa County	PV—196.8 kWp DC, yielding 255,882 kWh/year, covering an area of 1,275 m^2	The PV arrays are installed flush mounted using the Powerguard® PV roofing system, with 1080 Sanyo HIP-195 BA3 tiles, connected to two 100 kW Xantex inverters
Dutch Henry winery	Calistoga, Napa County	PV—16.1 kWp DC	150 Kyocera 125G roof mounted modules, tilted at 25° and connected to a Xantrex PV-20 inverter

(continued)

Table 5.2 (continued)

California			
Winery name	Region	Size	Details
Etude (Treasury)	Carneros, Napa County	PV—103.5 kWp DC, yielding 142,086 kWh/year	Flush roof mounted system
Far Niente winery	Oakville, Napa County	PV—478 kWp DC 400 kWp AC	The PV installation was the first winery application of "Floatovoltaics". The system consists of 2,296 modules (Sharp 208). 994 modules mounted above the irrigation pond and 1,302 modules ground mounted. The modules are connected to a 500 kW Satcon inverter
Flora Springs winery	Rutherford, Napa County	PV—74 kWp DC, yielding 100,000 kWh/year, covering an area of 600 m^2	435 SunTech 170 W ground mounted modules on the hillside behind the winery connected to two PVP 30 kW inverters
Frog's Leap winery	Rutherford, Napa County	PV—178.5 kWp DC, yielding 260,000 kWh/year	1,020 Sharp 175 W single-crystal silicon modules horizontally ground mounted over the leech field, connected to one 225 kW Xantrex PV-225 inverter
Green and Red winery	Chiles Valley, Napa County	PV—22 kWp DC	The PV installation provides 80% of the winery's electricity

(continued)

Table 5.2 (continued)

California

Winery name	Region	Size	Details
Grgich Hills Cellar	Rutherford, Napa County	PV—170.08 kWp DC, covering an area of almost 1,200 m^2	192 Kyocera KC 190GT modules mounted on the wine storage area, connected to 45 kW Xantrex inverter. 668 Kyocera KC 200GT modules mounted on the winery and tasting room, feeding into a 100 kW Satcon inverter, providing almost 100% of the winery's electrical needs
Hagafen Cellars	Oak Knoll, Napa County	PV—36.5 kWp DC, yielding 126,127 kWh/year	170 SunPower SPR-215 215Wp modules mounted on the roof of the winery. The modules are facing southwest at an incline of 25°. The PV modules are connected to a 30 kW Satcon inverter, producing 34.3% of the winery's total electrical requirement
Hall winery	St Helena, Napa County	PV installation covering approximately 3,900 m^2	Roof mounted system on the barrel cellar and fermentation building, supplying 35% of the building's electricity needs
Havens Wine Cellars	Yountville, Napa County	PV—46.5 kWp DC	246 solar modules mounted south facing on the winery roof
Honig vineyards and winery	Rutherford, Napa County	PV—163.8 kWp DC, yielding 277,000 kWh/year	819 Sanyo 200-watt modules ground mounted

(continued)

Table 5.2 (continued)

California			
Winery name	Region	Size	Details
Jarvis	Atlas Peak, Napa County	PV—107 kWp DC, yielding 155,000 kWh/year	520 SunPower SPR-205 modules ground mounted on a hillside connected to one Xantrex GT100 inverter
Keenan winery	Spring Mountain, Napa County	PV—41 kWp DC	BP Solar modules mounted in 29 arrays on pole mountings supplying 100% of the winery's power needs
Larkmead vineyards	Calistoga, Napa County	PV—not available	118 roof mounted modules supplying 30% of the winery's electrical needs
Leaf and Twig vineyard	St Helena, Napa County	PV—11 kWp DC	Ground mounted installation
Long Meadow Ranch winery	St Helena, Napa County	PV—50 kWp DC, yielding up to 8,000 kWh/month, covering an area of 475 m^2	Ground mounted system, located off-site at a pitch of 22° and 225° SW
Merryvale vineyards, for starmont winery	Carneros, Napa County	PV—277 kWp DC, 235 kWp AC, yielding 395,442 kWh/year, covering 2,060 m^2	1,632 Sharp 170 W modules roof mounted on a Unirac Sunframe, connected to two 135 kW Satcon inverters
Miner	Oakville, Napa County	PV—378 kWp DC, 323 kWp AC, yielding 562,950 kWh/year	14 arrays ground mounted into the steep southwest facing slope at a tilt of 35°. 1,750 Sharp 216 W PV modules are connected to one Advanced Energy Solaron 333 kW inverter
Nickel and Nickel (Sullenger vineyard)	Oakville, Napa County	PV—396 kWp DC, 330 kWp AC	1,904 Sharp modules on an adjustable tilt ground mounted system

(continued)

Table 5.2 (continued)

California			
Winery name	Region	Size	Details
Oakville Ranch winery	Oakville, Napa County	PV—137 kWp DC	Combination of ground (pumping station) and roof mounted (winery) systems, comprising 636 SunPower 215 W modules connected to 25 SunPower SPR 5200s inverters and two SunPower SPR 3200s inverters
Ovid winery	Oakville, Napa County	PV—33.25 kWp DC	175 ground mounted Sanyo 190 W modules located 200 m from winery at a pitch of 22° and connected to five Sunny Boy SMA 6,000 W inverters
Paloma winery	Spring Mountain, Napa County	PV—18 kWp DC, yielding 21,100 kWh/year	Mounted on the roof of barrelhouse
Patz and Hall	American Canyon, Napa County	PV—Almost 100 kWp DC, yielding 128,000 kWh/year	512 flush roof mounted modules providing 100% of the winery's electricity
Peju Province winery	Rutherford, Napa County	PV—126 kWp DC, yielding 157,610 kWh/year, covering about 930 m^2	720 Kyocera 175 W modules solar connected to one 125 kW SMA Sunny Boy inverter, supplying 36% of the annual energy requirement
Kent Rasmussen	St Helena, Napa County	PV—34 kWp DC	SunPower modules
Robert Sinskey	Stag's Leap, Napa County	PV—91 kWp DC, yielding 99,200 kWh/year	Two flush mounted arrays and one tilted array on the roof of the main buildings

(continued)

Table 5.2 (continued)

California

Winery name	Region	Size	Details
Saintsbury	Carneros, Napa County	PV—112 kWp DC, yielding 162,086 kWh/year covering an area of 650 m^2	560 Sanyo 200 W modules mounted on a car port structure connected to one 100 kW Xantrex PV100S-208 inverter
Schramsberg vineyards	Calistoga, Napa County	PV—yielding 466,806 kWh/year	1,665 ground mounted modules
Schweiger vineyards	Spring Mountain, Napa County	PV—39 kWp DC	174 SunPower 225s ground mounted modules connected to three SunPower SPR 6,000 W inverters; one SunPower SPR 5,000 W inverter and three SunPower SPR 4,000 W inverters
Seavey vineyard	Howell Mountain, Napa County	PV—10 kWp DC, yielding 20,075 kWh/year	64 modules and four inverters. Half of the modules are flush installed on a shed with a south facing roof and half on a custom-designed free-standing shade structure
Shafer vineyards	Stag's Leap, Napa County	PV—229.11 kWp DC	784 GE 165 W and 570 Sharp 175 W modules in combined roof and ground mounted installations, connected to various 45 kW and 30 kW Xantrex inverters and IG4500 Fronius inverter
Silver Oak Cellars	Oakville, Napa County	PV—275 kWp DC, yielding 429,589 kWh/year	1,464 ground mounted Sanyo 195 W modules connected to 25 Sunny Boy SB7000 US inverters

(continued)

Table 5.2 (continued)

California			
Winery name	Region	Size	Details
Silverado vineyards	Stag's Leap, Napa County	PV—98 kWp DC ground mounted and 96 kWp DC roof mounted, yielding 280,102 kWh/year	480 GE 200 W ground mounted modules connected to 16 Fronius 5,100 inverters and 450 GE 200 W roof mounted modules connected to 16 Fronius 5,100 inverters
Spottswoode estate	Spring Mountain, Napa County	PV—73 kWp DC, yielding 102,357 kWh/year	398 Sharp 180 W roof mounted modules
Staglin winery	Rutherford, Napa County	PV—164 kWp DC, yielding 172,166 kWh/year	Ground mounted installation over the winery leach field providing 100% of the winery's electrical needs
Stag's Leap (Treasury)	Stag's Leap, Napa County	PV—225.8 kWp DC, yielding 300,306 kWh/year	Flush roof mounted system
Stanly Ranch winery	Carneros, Napa County	PV—277 kWp DC	Providing 90–100% of the winery's annual electricity requirement
Sterling vineyards	Calistoga, Napa County	PV—72 kWp DC consisting of 55.5 kWp and 16.5 kWp systems, yielding 105,621 kWh/year	System A consists of 264 SunPower 210 W modules mounted via Powerguard roof tiles and eight SunPower inverters that power Sterling's aerial tram. System B consists of 72 SunPower 230 W modules and two SunPower inverters that power the winery's water treatment facility

(continued)

Table 5.2 (continued)

California			
Winery name	Region	Size	Details
Trefethen family vineyards	Oak Knoll, Napa County	PV—80 kWp DC, yielding 138,813 kWh/year	2 arrays; one at the winery and one at the office pond site. The winery site has 260 horizontal ground mounted (Conergy 175 W) modules connected to six SMA Sunny Boy 6 kW inverters. The pond site has 312 berm slope mounted (Conergy) modules connected to five SMA Sunny Boy inverters
Trinchero family estates	St Helena, Napa County	825 kWp DC (Roof mounted 761 kWp DC and Ground mounted 64 kWp DC), yielding 973,307 kWh/year and 92,597 kWh/year respectively	1,024 GE 200 W modules and 2,420 SunPower 230 W modules roof mounted and 320 GE 200 W ground mounted modules
Von Strasser	Calistoga, Napa County	PV—not available	186 ground mounted modules connected to six Sunny Boy inverters
V.Sattui winery	St Helena, Napa County	PV—34 kWp DC, yielding 46,250 kWh/year	198 modules mounted on the winery's red steel roof
ZD wines	Rutherford, Napa County	PV—125 kWp DC	712 Sanyo ground mounted modules, supplying 100% of the winery's electrical needs

(continued)

Table 5.2 (continued)

California			
Winery name	Region	Size	Details
Mendocino County			
Fetzer's Hopland winery	Mendocino Valley, Mendocino County	PV—899 kWp DC, yielding 1.1 million kWh/year	The PV installation supplies 80% of the bottling plant's electricity needs
Frey vineyards	Mendocino Valley, Mendocino County	PV—17 kWp DC	The PV installation supplies 75% of the winery's power
Handley Cellars	Anderson Valley, Mendocino County	PV—54 kWp DC, yielding 97,090 kWh/year	320 Kyocera KC200 modules connected to a 60 kW Solectria PVI inverter supplying 75% of the winery's power
Goldeneye winery	Anderson Valley, Mendocino County	PV—32.4 kWp DC, 28.6 kWp AC, yielding 49,460 kWh/year covering 195 m^2	144 roof mounted SunPower 225 W modules connected to six SMA 6,000 US inverters
Greenwood Ridge vineyards	Anderson Valley, Mendocino County	PV—not available	165 flush roof mounted modules
Navarro vineyards	Anderson Valley, Mendocino County	PV—31.5 kWp DC, yielding 45,430 kWh/year	Flush roof mounted modules connected to three inverters
Parducci	Mendocino Valley, Mendocino County	PV—99.66 kWp DC, yielding 200,000 kWh/year	592 Kyocera KC200GT modules connected to one 100 kW Xantrex PV-100-480-HE inverter
Philo Ridge vineyards	Anderson Valley, Mendocino County	PV—not available	A combined solar and wind installation
Paso Robles			
Castoro Cellars	Paso Robles	PV—18 kWp DC, yielding 28,100 kWh/year	108 Sharp 167 W modules flush roof mounted and connected to three SMA Sunny Boy 6,000 inverters. The installation offsets 50% of the winery's electrical usage

(continued)

Table 5.2 (continued)

California			
Winery name	Region	Size	Details
Clautiere vineyards	Paso Robles	PV—30 kWp DC	Flush roof mounted system, of setting the winery's energy costs by 80%
EOS	Paso Robles	PV—540 kWp DC (504 kWp tracking and 36 kWp fixed), yielding 1,062,948 kWh/year STC—60 flat plate collectors	2,880 Conergy AG S 175 MU modules on a single axis tracking of the system connected to 2×250 kW Xantrex inverters. 204 Conergy AG S 175 MU ground mounted fixed modules, connected to 6×6 kW Sunny Boy inverters. Roof mounted solar thermal collectors provide all the winery's hot water needs
J Lohr	Paso Robles	PV—756 kWp DC, yielding 1,524,184 kWh/year	4,320 ground mounted modules on a single axis tracking system. The installation is the largest PV tracking system winery in North America, covering an area acres, supplying 75% of the winery's electrical needs
L'Aventure vineyards	Paso Robles	PV—35.7 kWp DC, yielding 83,526 kWh/year	204 GE 175 W modules facing south and flush mounted on the winery metal roof, connected to eight Fronius 4,500 inverters
Meridian vineyards (Treasury)	Paso Robles	PV—In construction	Flush Roof mounted rated at 1.25 MWp DC is predicted to generate 1,750,629 kWh/year

(continued)

Table 5.2 (continued)

California

Winery name	Region	Size	Details
Saxum vineyards	Paso Robles	PV—not available	
Tablas Creek vineyard	Paso Robles	PV—35 kWp DC, yielding 48,000 kWh/year	140 Schott 250 W ground mounted modules at 20°, connected to 5 SMA Sunny Boy 6,000 inverters
Twin fawns vineyard	Paso Robles	PV—14.9 kWp DC	Fixed ground mount installation
Santa Cruz Mountain			
Bargetto winery	Santa Cruz Mountain	PV—3 kWp DC, yielding 4,500 kWh/year	PV installation used to power vineyard irrigation pumps
Cooper-Garrod estate	Santa Cruz Mountain	PV—17 kWp DC, yielding 22,000 kWh/year	96 tilted, roof mounted modules supplying 50% of the winery's power requirement
Mount Eden vineyards	Santa Cruz Mountain	PV—20 kWp DC	136 hillside mounted 185 W modules connected to 9 Sunny Boy inverters
Silver Mountain vineyard	Santa Cruz Mountain	PV—46 kWp DC	264 175 W roof mounted modules, located on a purpose built storage structure, connected to 6 Sunny Boy inverters
Storrs winery	Santa Cruz Mountain	PV—12.4 kWp DC	Ground mounted installation
Sierra Foothills			
Drytown Cellars	Sierra Foothills	PV—19.7 kWp DC	Roof mounted installation
Madrona vineyards	Sierra Foothills	PV—36 kWp DC	Roof mounted system, draping over the winery's roof on southern and western exposures, providing 100% of the winery's electrical requirement

(continued)

Table 5.2 (continued)

California

Winery name	Region	Size	Details
Sierra Vista winery	Sierra Foothills	PV—14.4 kWp DC, covering 140 m^2	Roof mounted Sharp 185 modules connected to Sunny Boy inverters
Terre Rouge	Sierra Foothills	PV—14.45 kWp DC, yielding 18,049 kWh/year	85 flush roof mounted GE 165 W modules on the winery metal roof, connected to seven SMA inverters, supplying 90% of the facility's electrical needs
Vino Noceto winery	Sierra Foothills	PV—10 kWp DC	Four 2.5 kW arrays mounted on the winery building facing southwest at a slope of 15°, connected to four Sunny Boy inverters. No roof reinforcement was necessary
Sonoma County			
Alexander Valley vineyards	Alexander Valley, Sonoma County	PV—49 kWp DC, yielding approximately 60,233 kWh/year	304 roof mounted Kyocera modules in three arrays installed on top of the winery connected to a 45 kW Xantrex inverter provides 60% of the facility's electricity
Asti winery (Treasury)	Alexander Valley, Sonoma County	PV—1190 kWp DC, yielding 1,549,629 kWh/year	Flush roof mounted system is the third largest solar installation at a winery in the USA
Chateau St Jean (Treasury)	Sonoma Valley, Sonoma County	PV—557 kWp DC, yielding 1,564,030 kWh/year	3,000 flush roof mounted modules

(continued)

Table 5.2 (continued)

California			
Winery name	Region	Size	Details
Cline Cellars	Carneros, Sonoma County	PV—411 kWp DC 351 kWp AC, yielding 586,000 kWh/year	1,974 Sharp 208 W modules, roof mounted on a Unirac Sunframe connected to one AE Solaron 333 kW inverter
Cougar's Leap winery	Lake County, Clear Lake	PV—not available	PV installation provides 100% of the facility's electricity
David Coffaro vineyard and winery	Dry Creek Valley, Sonoma County	PV—18 kWp DC	54 ground mounted fixed-tilt and 53 roof mounted Sharp ND-167U3 modules connected to 6 2.5 kW Sunny Boy inverters
DuMOL winery	Russian River, Sonoma County	PV—123.5 kWp DC, yielding 185,000 kWh/year, covering 650 m^2	392 roof mounted SunPower High-Efficiency (315 W) modules
Dutcher crossing	Dry Creek Valley, Sonoma County	PV—26 kWp DC, yielding 40,000 kWh/year	Four arrays of 153 Mitsubishi 170 W modules split between the south facing roof of the winery and on the ground in front of the winery connected to 4 6 kW Sunny Boy inverters supplying 85% of the winery needs

(continued)

Table 5.2 (continued)

California

Winery name	Region	Size	Details
Gundlach Bundschu winery	Sonoma Valley, Sonoma County	PV—127.25 kWp DC (92.25 kWp DC and 35 kWp DC)	System 1: 450 Kyocera 205 W west facing fixed ground mounted system covering 1.3 acres, rated at 92.25 kWp DC system connected to a 100 kW Satcon inverter, providing 60% of the winery power System 2: 154 Sharp 216 W modules mounted on pontoons on the pond connected to a Satcon inverter (+ 8 more fixed by the side with a Sunny Boy inverter). The second floating array (Floatovoltaics) of its kind in the world, it provides 100% of the power needed to run the water reclamation system
Jacuzzi	Carneros, Sonoma County	PV—124 kWp DC, 103 kWp AC, yielding 185,130 kWh/year in fixed mode and 222,156 kWh/year in tracking mode	748 Mitsubishi 165 W modules mounted on a combination of fixed ground mount, fixed pole mount and single axis tracker, connected to two 50 kW Satcon inverters
Kaz winery	Sonoma Valley, Sonoma County	PV—approximately 5 kWp DC	28 flush roof mounted modules connected to two Sunny Boy inverters

(continued)

Table 5.2 (continued)

California

Winery name	Region	Size	Details
Kunde family estate winery	Sonoma Valley, Sonoma County	STC—covering 93 m^2	50 flat plate roof integrated solar thermal system producing 50% of the hot water used for sterilization and cleaning processes in winery. The collectors are tilted at 15° facing due south and indirectly connected via a glycol loop to a 3,785 l storage tank
Lancaster estate	Alexander Valley, Sonoma County	PV—100 kWp DC, yielding 151,997 kWh/year	Six arrays of 474 ground mounted Sanyo 210 W modules
Lavender Hill vineyards	Dry Creek Valley, Sonoma County	PV—5.0 kWp DC, yielding 17,885 kWh/year	Ground mounted installation
Marimar Torres estate	Green Valley, Sonoma County	PV—yielding 37,600 kWh/year	Ballasted roof mounted system connected to 4 Sunny Boy inverters
Medlock Ames	Knights Valley, Sonoma County	PV—84 kWp DC, yielding 140,000 kWh/year	UniRac framework mounted Kyocera modules connected in six arrays to a range of invertors
Merry Edwards	Russian River Valley, Sonoma County	PV—35 kWp DC	162 SunPower 215s roof mounted modules connected to seven SPR 4,600s inverters
Moshin vineyards	Russian River Valley, Sonoma County	PV—48 kWp DC	200 roof mounted 240 W modules connected to 6 Sunny Boy inverters

(continued)

Table 5.2 (continued)

California			
Winery name	Region	Size	Details
Peay vineyards	Sonoma Coast, Sonoma County	PV—42 kWp DC	240 roof mounted SunPower modules on the southwest facing portion of the winery roof. There is also a small 4.2 kW solar PV installation alongside the winery reservoir
Preston winery	Dry River Creek, Sonoma County	PV—37 kWp DC	Mounted on winery roof
Quivira vineyards	Dry River Creek, Sonoma County	PV—55 kWp DC	Approximately 300 Sharp 185 W roof mounted modules providing 100% of the winery's electricity
A Rafanelli	Dry Creek Valley, Sonoma County	PV—not available	Roof mounted installation
Raymond Burr vineyards	Dry Creek Valley, Sonoma County	PV—37 kWp DC, 31 kWp AC, yielding 45,000 kWh/year	212 roof mounted Sharp 175 W modules connected to seven PVP 5,200 inverters
Redwood ranch and vineyards	Alexander Valley, Sonoma County	PV—35.6 kWp DC	Two ground mounted arrays of 216 GE 165 W modules connected to six Fronius IG 5,100 solar inverters
Ridge Lytton Springs	Dry River Creek, Sonoma County	PV—65 kWp DC, yielding 85,000 kWh/year	400 roof mounted modules using the Power light system, connected in two arrays, tilted at 35° on the 17° sloped winery roof, connected to two 30 kW Xantrex kW inverters, supplying 85% of the winery's electricity

(continued)

Table 5.2 (continued)

California

Winery name	Region	Size	Details
Rodney strong vineyards	Russian River Valley, Sonoma County	PV—766 kWp DC, yielding almost 860,000 kWh/year and covering 7,430 m^2	4,032 roof mounted SunPower modules connected to three inverters. The modules are mounted at 5° on the barrelhouse roof, a few inches above the roof to give both shade and cooling airflow
Schug Carneros estate winery	Carneros, Sonoma County	PV—54.2 kWp DC (34.5 kWp DC and 19.7 kWp DC), yielding 52,538 kWh/year and 29,780 kWh/year for the winery and vineyard, respectively	Two ground mounted fixed cantilever carport PV arrays. System 1: 154 Sharp ND-224 W modules connected to six SMA Sunny Boy 8,000 US inverters. System 2: 88 Sharp ND-224 W modules connected to three SMA Sunny Boy 8,000 US inverters. Both systems are designed to produce 100% of the winery's and vineyard's electricity needs
Seghesio family vineyards	Russian River Valley, Sonoma County	PV—157 kWp DC, yielding 236,471 kWh/year	Combination of flush and tilt roof mounted modules
Skipstone Ranch	Alexander Valley, Sonoma County	PV—35 kWp DC	130 ground mounted modules
Sonoma Wine Co. (custom crush facility)	Graton, Sonoma County	PVT—272 kWe + th, yielding 64,000 kWh/year electrical and 366,340 kWh/year thermal	15 ground mounted Cogenra SunBase™ concentrating collectors in a single axis tracking system

(continued)

Table 5.2 (continued)

California			
Winery name	Region	Size	Details
St. Francis winery	Sonoma Valley Sonoma County	PV—457 kWp DC	Sharp and Sanyo modules connected to two Xantrex inverters, providing 40% of the winery's electricity
Topel winery	Healdsburg, Sonoma County	PV—12.6 kWp DC	64 Kyocera roof mounted modules
Trione vineyards and winery	Alexander Valley, Sonoma County	PV—39 kWp DC, 33 kWp AC, yielding 53,477 kWh/year	210 roof mounted Sharp 187W modules connected to five SMA SB 7,000 US inverters
Wasson vineyards	Alexander Valley, Sonoma County	PV—not available	
Wattle creek	Alexander Valley, Sonoma County	PV—not available	Solar installation supplies 100% of the winery's power
Wellington	Sonoma Valley Sonoma County,	PV—30 kWp DC, 26 kWp AC, yielding 40,586 kWh/year	174 roof mounted Mitsubishi 170W modules connected to five SMA SB 6,000 US inverters
Wild Hog vineyard	Russian River Valley, Sonoma County	PV—2 kWp DC	Combined solar PV and hydro electricity installation. Small stand-alone PV, battery storage connected to a trace 4,024 inverter. The hydro system is a 35 psi twin nozzle pelton water wheel rated at approximately 1 kWp
Williams Selyem estate winery	Russian River Valley, Sonoma County	STC—14 solar thermal collectors PV—54 kWp DC	14 roof mounted Heliodyne Gobi 408 flat plate collectors provide approximately 2,460 l of hot water/day. 226 roof mounted modules provide up to 33% of the facility's electrical needs

(continued)

Table 5.2 (continued)

California			
Winery name	Region	Size	Details
South Coast			
Hamilton Oaks winery	Trabuco Canyon, South Coast	PV—13 kWp DC	Ground mounted installation
Shale Canyon Wines	Boulder creek, South Coast	PV—8.4 kWp DC	48 Mitsubishi (175 W) ground mounted modules connected via 3 Outback FM80 charge controllers to a HUP Solar One 1,690 AH 33/48 V battery with 4 Outback VFX3648 Inverters rated at 3.6 kW each (48 Volt) linked to an Outback X-240 4 kVA Transformer. This system enables the winery to be 100% off-grid

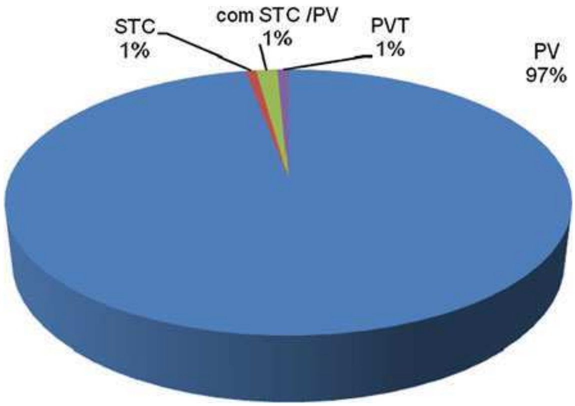


Fig. 5.7 Types of solar installations in wineries in California

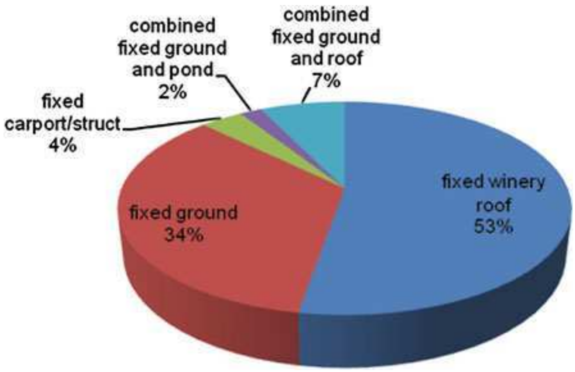


Fig. 5.8 Photovoltaic mounting arrangements in wineries in the Napa Valley, California

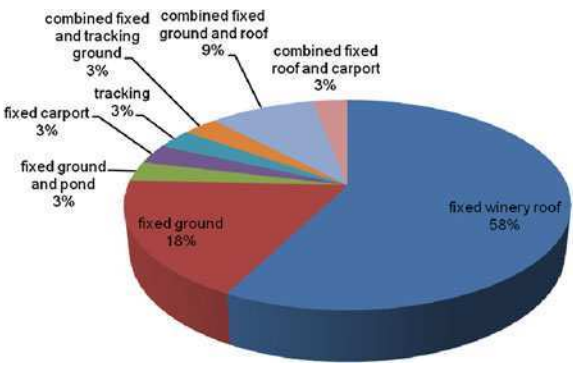


Fig. 5.9 Photovoltaic mounting arrangements in wineries in Sonoma County, California

Like California, the solar wineries located in the remaining states tend to opt for photovoltaic installations (over 93%), following a similar trend in mode of installation and component selection. The average size of a winery PV installation in the rest of the USA is 28.9 kWp (Fig. 5.14).

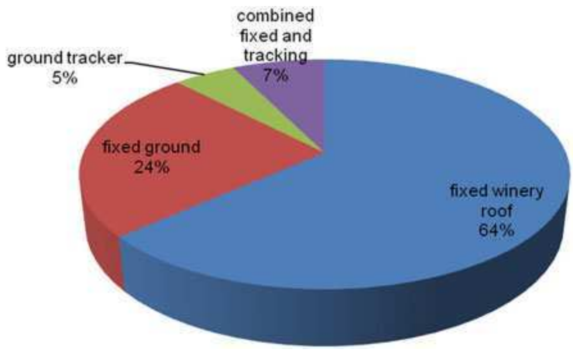


Fig. 5.10 Photovoltaic mounting arrangements in wineries in the rest of California

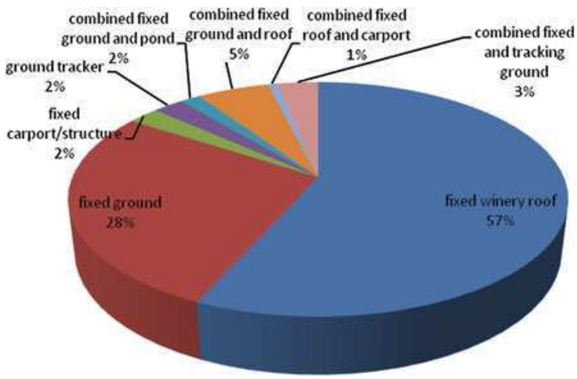


Fig. 5.11 Photovoltaic mounting arrangement for Californian wineries

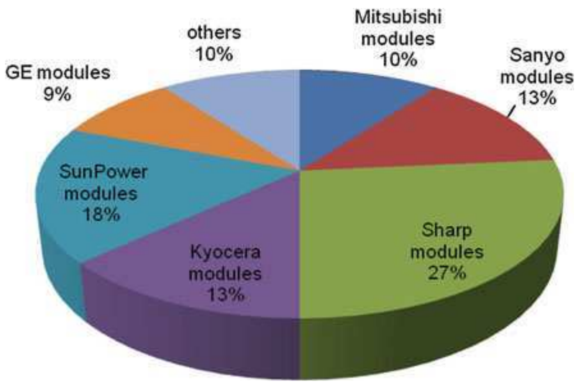


Fig. 5.12 Module type by manufacturer for Californian solar wineries

5.2.2.2 Wineries Using Solar Energy in Rest of the New World

There are only 26 indentified solar wineries in the rest of the new world, of which 11 are located in Australia and 7 in Chile. Table 5.4 lists the details of the solar wineries in the rest of the new world. It is difficult to access information relating to

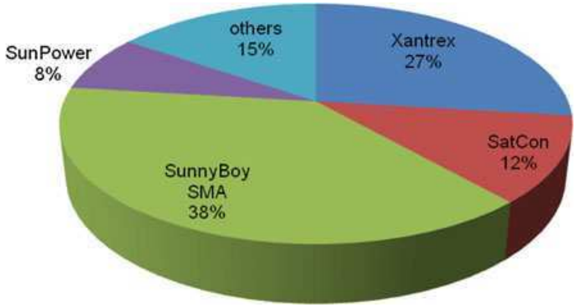


Fig. 5.13 Inverter type by manufacturer for Californian solar wineries

their respective solar installations, but it is evident that solar thermal systems are more prevalent and the photovoltaic installations tend to be smaller in comparison to the solar systems installed in wineries in the USA.

Detailed information, relating the system parameters for solar wineries throughout the remaining new world is difficult to attain. However, it is clear to observe that a significantly larger percentage of the installed systems are solar thermal (Fig. 5.15). There may be numerous specific reasons for this difference, but one important factor relates to the level of subsidy that exists both in Europe and the USA. Without significant financial assistance, solar thermal is more economically viable and thus offers a better return for the winery.

Wineries Using Solar Energy in Canada

There are 356 wineries in Canada [9] as of November 2008. British Columbia has the most wineries with 182 wineries, Ontario has 108 and Quebec has 52 with 14 distributed between the remaining 5 provinces. Only two significant solar wineries are known to exist in all of Canada.

Wineries Using Solar Energy in Australia

In April 2010, there were 2,420 commercial wineries operating in Australia [5], with a significant distribution within all the states/territories. The following is a simple breakdown of the distribution.

- Victoria 724
- Southern Australia 648
- NSW and ACT 467
- Western Australia 372
- Queensland 111
- Tasmania 98

Given the number of wineries, it is surprising that only 11 solar wineries are known to exist in all of Australia. Victoria has five solar wineries, with two each in Southern Australia, NSW and Western Australia, giving a solar winery representation of less than 0.5%.

Table 5.3 Details of the solar wineries in the rest of the USA

Rest of the USA			
Winery Name	Region	Size	Details
Priam vineyards	Colchester, Connecticut	PV—8 kWp DC, covering 133 m^2	50 ground mounted modules on a fixed tilted array. New England's first solar powered winery
Persimmon Creek vineyards	Rabun County, Georgia	PV—8 kWp DC, yielding 11,200 kWh/year	36 roof mounted SunPower modules located on the roof of the winery, providing approximately 50% of the facility's power
Camas Prairie winery	Moscow, Idaho	PV—5 kWp DC	Idaho's first solar powered winery. Roof mounted modules providing 20% of the winery's electricity needs
Ten Spoon winery	Rattlesnake valley, Montana	PV—4 kWp DC STC—30 evacuated Thermomax tubes	Two PV tracking systems
Paumanok vineyards	Long Island, New York	PV—10 kWp DC	SunPower 210 W roof mounted modules, providing 25% of the winery's electricity needs
Peconic Bay winery	Long Island, New York	PV—39.8 kWp DC, yielding 47,826 kWh/year	180 module installation, providing 70% of the winery's electricity needs
Sheldrake point winery	Ovid, New York	PV—14.85 kWp DC	90 SunWize 165 W roof mounted modules connected to five Sunny Boy 2,500 Inverters

(continued)

Table 5.3 (continued)

Rest of the USA			
Winery Name	Region	Size	Details
Stoutridge vineyard	Marlboro, New York	PV—40 kWp DC, covering 280 m^2	Roof mounted array on a south facing roof using SunPower modules supplying the building with 100% of its electrical needs
RayLen vineyards and winery	Mocksville, North Carolina	PV—9.88 kWp DC	104 NexPower thin film 95 W modules mounted in two fix tilted arrays connected to two SMA Sunny Boy 5,000 W inverters
Bethel Heights vineyard	Willamette Valley, Oregon	PV—60 kWp DC	126 ground mounted modules supplying 40% of the electricity needed for the winery
Domaine Drouhin	Willamette Valley, Oregon	PV—94.5 kWp DC, yielding 101,100 kWh/year	Ground mounted installation. The largest solar system in the Oregon wine industry
Elk Cove vineyards	Willamette Valley, Oregon	PV—38.8 kWp DC, yielding 41,500 kWh/year	Grid tied roof mounted installation
Illahe vineyards	Dallas, Oregon	PV—not available	PV installation supplying 50% of the winery's needs coupled with being one of Oregon's few horse-powered vineyards

(continued)

Table 5.3 (continued)

Rest of the USA

Winery Name	Region	Size	Details
Left Coast Cellars	Rickreall, Willamette Valley, Oregon	PV—83 kWp DC	Two PV installations, one 21 kWp DC ground mounted system supplying the guest cottage, front gate and estate irrigation needs. The other is a 62 kWp DC roof mounted system supplying the winery
Lemelson winery	Yamhill County, Oregon	PV—49.7 kWp DC, yielding 53,200 kWh/year	Ground mounted installation
Mahonia vineyards	South Salem, Oregon	PV—16 kWp DC	Roof mounted installation
Ponzi vineyards and winery	Willamette Valley, Oregon	PV—not available	Roof mounted installation
River's edge winery Vineyards	Elkton, Oregon	PV—yielding approximately 8,600 kWh/year	36 roof mounted modules generating about 50% of the winery's electrical needs
Sokol Blosser	Willamette Valley, Oregon	PV—23.8 kWp DC	Ground mounted installation providing 33% of the winery's electricity needs
Stoller vineyards	Dundee Hills, Oregon	PV—46 kWp DC, yielding 57,000 kWh/year	224 roof mounted modules mounted on the winery's main south facing roofs, providing up to 50% of the facility's electricity
Torii Mor winery	Dundee Hills, Oregon	PV—67.5 kWp DC	Two roof mounted systems, one on the fermentation room (47.5 kWp DC) and one on the tank room (20 kWp DC)

(continued)

Table 5.3 (continued)

Rest of the USA

Winery Name	Region	Size	Details
Winderlea vineyard and winery	Dundee, Oregon	PV—13 kWp DC STC—not available	Day four energy PV modules and solar water heating collectors mounted on the south facing shed roof
Hopewell vineyards	Lower Oxford, Pennsylvania	PV—27.7 kWp DC, yielding 36,070 kWh/year	132 ground mounted 210 W Shuco modules
J. Maki winery	Elverson, Pennsylvania	PV—10 kWp DC	Solar tracking system that produces 50% of the winery's electrical needs
Stargazers vineyard	Coatesville, Pennsylvania	PV—9 kWp DC, yielding 4,800 kWh/year	30 roof mounted BP modules installed on the south facing winery roof at a 26° slope
HRH wineries	Humboldt, Tennessee	PV—16.8 kWp DC, yielding 22,543 kWh/year	78 Sharp 216 W modules connected to three SMA Sunny Boy 6,000 W inverters and Sunny Boy Web Box monitoring system
Sunset Hills vineyard	Purcellville, Virginia	PV—16.8 kWp DC, yielding 25,000 kWh/year	154 roof mounted modules on the south facing roofs of their case storage and tasting room barns
Wilridge winery	Seattle, Washington	PV—10 kWp DC	44 ground mounted SolarWorld 230 W modules connected to two inverters

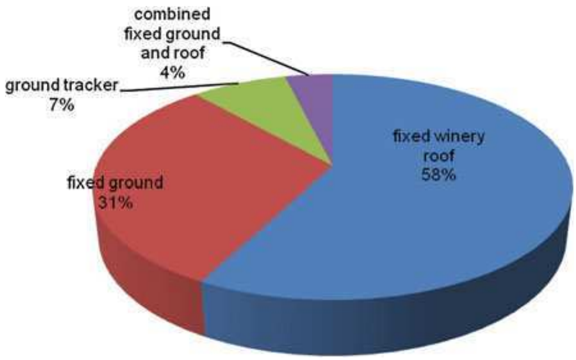


Fig. 5.14 Photovoltaic mounting arrangement for wineries in the rest of the USA

Wineries Using Solar Energy in Africa

The main wine producing regions in Africa are limited to the extreme north and south of the continent. The once thriving wine industry in North African is now almost negligible in global output due to Muslim beliefs, with only a reduced number of commercial wineries located in Egypt, Morocco, Tunisia and Algeria. South Africa, however, is the 8th largest producer in the world and its 561 wineries are mostly located in the Western Cape Province, with some in the Northern Cape and Free State [3]. In solar winery terms, there are only three wineries that have a significant solar installation, one in Tunisia, the other two in South Africa.

Wineries Using Solar Energy in South America

Wine and winemaking in South America has a longer history than anywhere else in the new world. There are thousands of wine producers in South America, the vast majority of which are in Chile and Argentina. There are approximately 250 large commercial wineries in Chile whilst Argentina has 1,196 commercial wineries [8]. From these totals, only seven wineries that utilise significant active solar collection are known, all of which are located in Chile.

Wineries Using Solar Energy in New Zealand

New Zealand has over 400 commercial wineries [8], of which only 2 utilise any form of active solar collection.

Wineries Using Solar Energy in Asia

Asia (excluding the Mediterranean regions) is a relatively new wine producing area (although recorded history dates the introduction of wine grapes by the Russians almost 2000 years ago). The main regions of winemaking are China,

Table 5.4 Details of the solar wineries in the rest of the new world

Rest of the new world			
Winery name	Region	Size	Details
Fermoy estate	Margaret River, WA, Australia	STC—three Solarhart collectors	With auxiliary gas boosting, the solar installation is capable of producing 1,000 l of hot water at 88°C/day
Ferngrove winery	Frankland River, WA, Australia	STC—rated at 10 kW	Eight solar collectors provide the winery with the needed 5,000–10,000 l of hot water/day at 90°C
Sarsfield estate	Sarsfield, Victoria, Australia	PV—not available	Solar and wind energy
Banrock station	Kingston-on-Murray, SA, Australia	PV—yielding approximately 1,100 kWh/year	Three (six module) pole mounted tracking arrays located beside the Wine and Wetland visitor centre
Nuriootpa winery (Elderton Wines)	Barossa valley, SA, Australia	PV—30 kWp DC, yielding approximately 55,000 kWh/year	168 flush roof mounted modules, covering an area of 216 m^2
Paradigm Hill	Mornington Peninsula, Victoria, Australia	PV—9.45 kWp DC, yielding 13,850 kWh/year	54 ground mounted modules on a fixed tilted array
Langanook wines	Central Victoria, Australia	PV—not available	PV powered winery
Pulpit rock estate	Southern Highlands, NSW, Australia	PV—not available STC—not available	Combination of solar and wind powered winery producing hot water and electricity
Dog rock winery	Crowlands, Victoria Australia	PV—not available STC—not available	Combination of solar and wind powered winery producing hot water and electricity
Wolseley wines 80 barrels last year	Paraparap, Victoria Australia	PV—2 kWp DC	PV powered winery

(continued)

Table 5.4 (continued)

Rest of the new world

Winery name	Region	Size	Details
Belgrave park winery	Cobargo, NSW, Australia	PV—3 kWp DC	Three (six module) roof mounted, tilted arrays solar power system, which provides most of the winery's electricity
Burrowing Owl estate winery	Oliver, British Columbia, Canada	STC—not available	30 roof mounted flat plate collectors, producing DHW, building space heat and ground loop support via a 3,600 l tank
Harwood estate vineyards	Ontario, Canada	PV—not available	Ground mounted tilted modules
Redtail vineyard	Ontario, Canada	PV—not available	Six ground mounted tilted modules. Canada's first "off-grid" winery
Agustinos winery	Biobío Valley, Chile	STC—not available	Roof mounted flat plate collectors to produce hot water used in wine production and the operation of the winery
Cono Sur	Colchagua Valley, Chile	PV—not available	Combination of solar and wind powered winery producing hot water and electricity
Emiliana	Casablanca Valley, Chile	STC—not available	Two ground mounted flat plate collectors to produce hot water for use in the winery
Errázuriz winery	Valle de Aconcagua, Chile	STC—not available	21 solar thermal collectors to heat 8,000 l between 60 and 70°C

(continued)

Table 5.4 (continued)

Rest of the new world			
Winery name	Region	Size	Details
Los Vascos winery	Colchagua valley, Chile	STC—196 m^2	Two separate solar thermal systems; system 1 has eight solar thermal collectors (16 m^2) supplying 600 l/day of hot water for cleaning equipment, saving 70% of the energy previously used; system 2 has 90 solar thermal collectors (180 m^2) mounted on the winery roof to obtain the thermal requirements of tanks during the malolactic fermentation of wine, providing pre-heat for 10,500 l/day
Matetic vineyards	Rosario Valley, Chile	STC—not available	Solar water heating is used to offset 30% of their propane usage in heating water for use in the winery
VIK	Millahue, Chile	PV—not available	
Sula vineyards	Maharashtra, India	STC—not available	Solar thermal collectors to meet the winery's hot water requirements
Yealands estate winery	Marlborough, New Zealand	STC—47 kWh/day	Evacuated tube solar collectors providing hot water for the domestic hot water needs of the winery

(continued)

Table 5.4 (continued)

Rest of the new world			
Winery name	**Region**	**Size**	**Details**
Orinoco vineyards	Moutere Hills, Nelson, New Zealand	PV—not available	PV powered winery
Backsberg Wine Cellars	Paarl, South Africa	PV—not available	PV powered winery
Villiera wines	Stellenbosch, South Africa	PV—132 kWp DC, yielding approximately 265,000 kWh/year and covering 900 m^2	539 roof mounted polycrystalline modules across three roof structures
Domaine Neferis, part of Calatrasi winery Grombalia in Italy	Tunisia	STC—Concentrating system covering 88 m^2	A 16 m long Fresnel concentrator providing process heat for an absorption chiller unit providing process coolth for the winery

Fig. 5.15 Types of solar installations in wineries in the rest of the new world

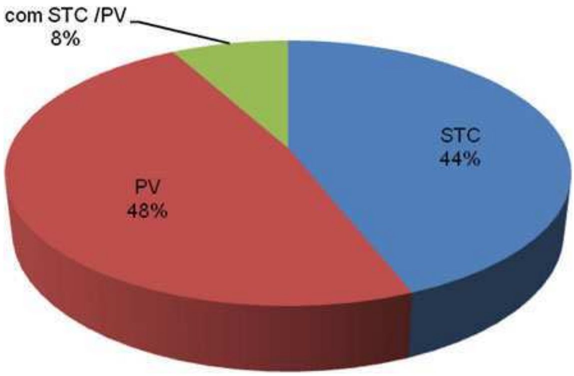
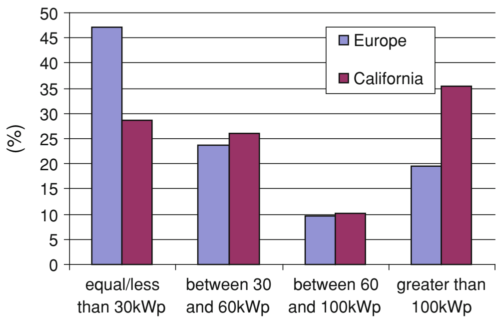


Fig. 5.16 Solar PV winery installation size for Europe and California



India, Japan, Indonesia and Thailand. Although small in number by western standards, there were a reported 800 wineries operating in Asia in 2008 [6]. Only one winery has been identified has having a significant solar installation.

5.2.3 Complete World Summary

In real terms, the vast majority of solar systems are in either the USA (specifically California) or Europe. Both these regions represent almost 92% of all the catalogued solar wineries, with 57.5% in the USA (48% in California) and over 34% in Europe. The size of solar PV system installed is the biggest factor separating the USA (California) and Europe. Figure 5.16 illustrates the variation in system size at the upper and lower end of kWp installed. Europe has a significantly larger proportion of systems under 30 kWp, whilst California has more systems that are greater than 100 kWp. The average size of a Californian winery installation is 169.1 kWp whilst the average size for a European installation is 77.8 kWp. As previously mentioned, a simple reason for these differences is due to the economic incentives that exist in each region, although a number of practical factors also contribute.

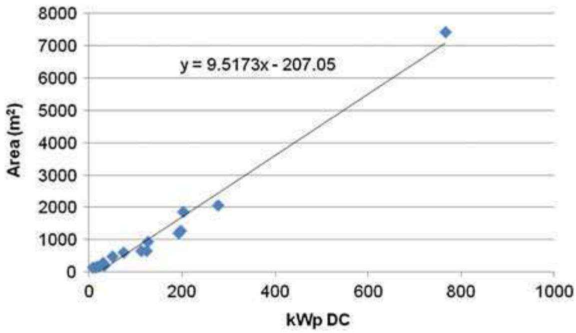


Fig. 5.17 Relationship of installed kWp DC against module area for solar wineries in the USA

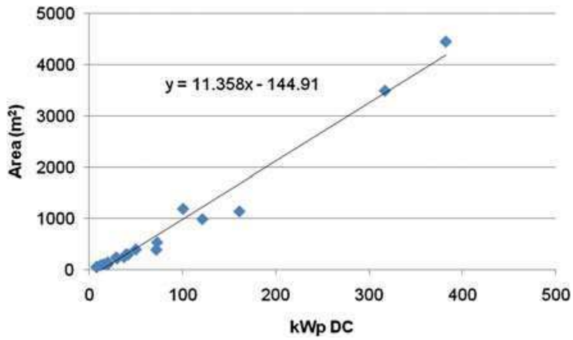


Fig. 5.18 Relationship of installed kWp DC against module area for solar wineries in Europe

From Figs. 5.17 and 5.18, the average module area per kWp DC is greater for European solar winery installations when compared to US installations. On average, a winery in Europe requires 11.36 m^2 whilst an American winery only requires 9.52 m^2. It is difficult to exactly determine why this is, but it is probably due to the age and type of systems installed. Installations in the USA, tend to be more recent and therefore the modules selected are slightly more efficient per unit area. In addition, from the study of the preferred type of module used, thin film technology is more common in Europe, perhaps due to factors relating to cost and a greater occurrence of diffuse sky conditions.

From Figs. 5.19 and 5.20, American solar winery installations produce more power (kWh)/year/kWp DC compared to European solar winery installations. On average, a winery in Europe produces 1235 kWh/year/kWp DC installed whilst an American winery produces 1456 kWh/year/kWp DC installed. The reason for the difference can again be explained through more recent installations and thus modern (more efficient) modules and BOS, but the existence of a better average solar resource in the USA is also a significant factor. Whilst the average size of module installed varies little between Europe and California (183–192 W, respectively), the rated inverter capacity again demonstrates the selection of larger PV BOS systems in California. On average, an inverter in a European solar winery will be designed for 48.5 kWp DC whilst a Californian installation will have an inverter designed for 81.6 kWp DC.

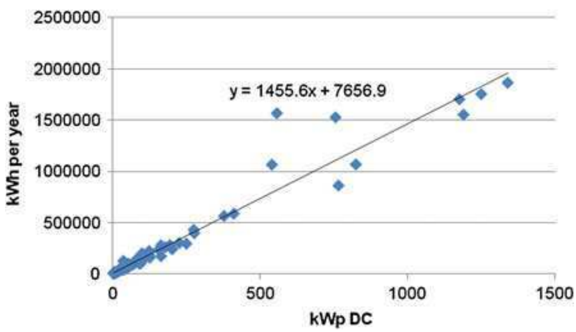


Fig. 5.19 Relationship of installed kWp DC against kWh/year for solar wineries in the USA

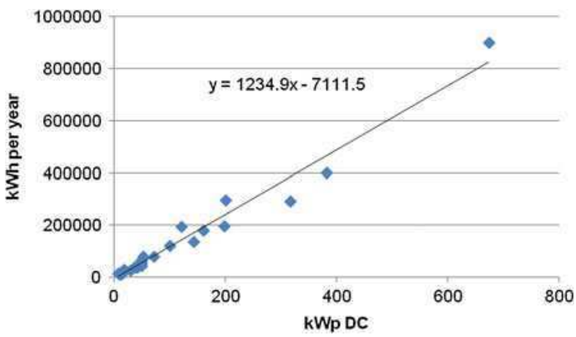


Fig. 5.20 Relationship of installed kWp DC against kWh/year for solar wineries in Europe

5.3 Case Study Solar Wineries

Section 5.2 briefly catalogues the range of wineries globally that have installed a substantial solar collecting system. The following section presents in greater detail a number of solar wineries with their respective solar installations. These case studies have been selected to present the reader with an appreciation of the range of different systems that have been installed globally, covering the old and new world wine producing regions. A total of 19 wineries are represented; 5 old world (1 German, 2 Italian, 1 Spanish and 1 Austrian) and 14 new world (from California, North Carolina and Australia). The installations cover large industrial style wineries, contract wineries, co-operative run wineries, boutique wineries and family run wineries and span building types as different as new state-of-the-art facilities to fifteenth century palaces. The case studies cover a range of solar designs and systems including; generic system type (solar thermal, solar cooling, PV and PVT; installation (PV only, solar thermal only or combination); mounting arrangements (roof, ground, pond or BIPV); operation ((fixed—flush or tilted) or (tracking—one or two axis)); different module and inverter components and configurations; connection (grid tied, building only or stand-alone); finance (grants, feed in tariff, HPPAs and others).

Each case study gives the reader an overview of the winery covering topics such as the location, type and history of the winery, their winemaking philosophy, wine types and production processes. The basic description of the solar facility is presented and, depending upon the solar facility, covers the following:

- PV (components (modules, inverters, other BOS), rated capacity, coverage, annual yield, mounting format, exposure (orientation, shading etc.).
- Thermal (components (thermal collector, storage tank, control), rated capacity, coverage, annual yield, mounting format, exposure (orientation, shading etc.)).

Where possible the economic backdrop is detailed covering the cost to install, any grants, FITs or other financial incentives used, annual savings and potential payback period. The case study format also provides feedback from the winery based on the monitored variables and the user's experience (installation, breakdown, failure, operation, feedback, security, maintenance). Other environmental or energy based systems or processes that are unique and provide a backdrop to the winery's operation are included, ranging from straw bale construction to passive rock cooling and bio-algae production to enhanced day lighting features. In addition to the written word, pictures, diagrams, specific detailing, schematics, tables and graphs are all used to give the reader a fuller appreciation of the winery and installed solar system.

5.3.1 Solar Case Studies in the Old World

5.3.1.1 Case Study Alois Lageder, Bolzano, Italy

The Alois Lageder winery is a beautiful example of traditional, old winemaking values embracing new, innovative techniques in sustainable wine production. Entering the winery through the fifteenth century gate of the old Tòr Löwengang complex, you enter into a winery that represents the future for the European, 'old world' wine industry (Fig. 5.21).

The original historical buildings, extensively renovated in the 1800s, were augmented by a state-of-the-art modern winemaking facility in 1996. The new winery was designed according to construction principles that emphasised low energy consumption and natural materials. The conceptual operation of the winery is based around two elementary natural principles: the force of gravity and the circular form. Using a gravity based winery design eliminates the need for pumps and other mechanical methods of moving the grapes, must and wine and using a circular tank arrangement minimises travel distances. Paramount to the operation of the winery is the efficient use of energy. Alois Lageder was very much aware of inconsiderate and irrational use of technology within the wine industry and therefore careful attention was given to equipment that provided effective energy usage and/or was sourced using alternative energy systems. Central to this concept are the solar PV and thermal installations (Figs. 5.22, 5.23 and 5.24).

Fig. 5.21 Historic entrance into the Alois Lageder winery

Fig. 5.22 The combined PV and solar thermal installation mounted on the integral winery roof/shading structure (reproduced by kind permission of Alois Lageder)

The PV installation at Alois Lageder was completed in two stages (with a 3rd 10 kWp currently being installed and plans for a further 150 kWp in the pipeline). The first phase, installed in 1996, consisted of 160 Solar Fabrik (110 W) modules mounted onto a building-integrated roof/shading structure facing south-southeast at a tilt of 30°. The modules cover an area of 130 m^2 and are rated at 17.5 kWp, producing approximately 15,000 kWh/year. The second phase, installed in December 2006, consists of 156 Solar Fabrik (127 W) modules mounted onto the same structure, covering an area of 125 m^2, rated at 19.8 kWp, producing approximately 23,000 kWh/year. Both installations combined have a rated DC output of 37.3 kWp, connected into the winery's electrical distribution grid via a range of differently rated SMA Sunny Boy inverters. The inverters are located on

Fig. 5.23 Winery and integral roof/shading structure following the first phase PV installation (reproduced by kind permission of Alois Lageder)

Fig. 5.24 Phases 1 and 2 and solar thermal installation (reproduced by kind permission of Alois Lageder)

the underside of the supporting roof/shading structure, as shown in Fig. 5.25 producing 38,000 kWh/year. The PV installation produces an estimated 14.2% of the winery's total power consumption.

The first phase, when first activated, was the first solar winery and most modern installation in north-eastern Italy and was also the first in Italy to be financed by private funds. At a cost of approximately €125,000, with a 30% capital grant coming from the south tirol government, the system had a calculated payback of nearly 25 years. The second phase, at a cost of €115,000 made advantage of a 20% national grant contribution coupled with a FIT of €0.44/kWh, which brought the payback period down to less than 10 years.

In addition to the solar PV installation, the winery takes advantage of solar thermal collection, both passively and through active collection. An atrium feature is used to directly provide passive solar gain for the office and administration areas, increasing the daylight fraction and development of stack effect natural ventilation during the summer months. On the same building-integrated roof/shading structure that the PV modules are mounted upon, 14 flat plate thermal collectors covering 24 m^2 and capable of collecting 17.5 kW at a peak solar flux

Fig. 5.25 Inverters positioned on the underside of the supporting roof/shading structure

1000 W/m^2 are mounted (Fig. 5.22). The collectors are connected to two 1,500 l tanks which supply the winery with hot water, for sanitation and cleaning requirements. If necessary, heat can be re-directed to supply heat to the office's space heating circuits, when suitable conditions prevail.

As previously mentioned, the Alois Lageder winery employs a wide range of innovative energy efficient systems and equipment. Perhaps one of the most revolutionary in a winery context is the use of active rock face for winery temperature regulation. The winery abuts a large natural rock wall providing a natural heat store which has a constant temperature of 10°C throughout the year. The winery was deliberately designed to create a cavity between the rock face and the building's concrete structure, from which a ducted supply and extract ventilation installation can distribute pre-heated or pre-cooled air throughout the winery (Fig. 5.26). Two reversible heat pump/refrigeration units ensure that air is conditioned to meet the winery requirements and along with another refrigeration unit, the hydronic system can meet the total heating and cooling requirements for winery space environment, temperature regulation of the wine during fermentation and other vinification processes and hot water production for washing and cleaning tasks. This system ensures that the winery does not burn fossil fuels, avoiding subsequent products of combustion. The entire heating and cooling installation is computer controlled giving a very closely controlled and thus efficient/effective operation.

5.3.1.2 Case Study Nosio Facility, MezzaCorona Group, Trento, Italy

Located in heart of the Dolomites along the Italian Alps, the state-of-the-art MezzaCorona (Nosio) facility, just one of the three main wineries operated by the MezzaCorona Group, collects the grapes produced by their 1,300 growers and

Fig. 5.26 Innovative use of natural rock face heat/coolth storage

Fig. 5.27 The 11 ha MezzaCorona (Nosio) site sitting in the heart of the Dolomites, surrounded by the co-operative's vineyards (reproduced by kind permission of the MezzaCorona group)

harnessing the expertise of over 100 years of traditional winemaking they produce elegant, crisp wines according to the company's 100% single varietal philosophy. The MezzaCorona (Nosio) winery is the perfect example of excellence in wine production.

The MezzaCorona winery (later Group) was founded in 1904 and was one of the first association of wine producers in Italy. Today it has over 2,400 ha of vineyard and produces nearly 45 million l of wine annually. To meet this demand in 1995 the company moved into an 11 ha site (Fig. 5.27) with a state-of-the-art winery complex covering over 11,250 m^2. Rather than have one building, the co-operative opted to build a series of buildings which would house the winery, sparkling wine production facilities, an auditorium, offices and an area for direct sales. An architectural theme running through the individual buildings closely links them to the surroundings, creating an obvious unity between the environment and the buildings. Following this philosophy, the group has recently invested in

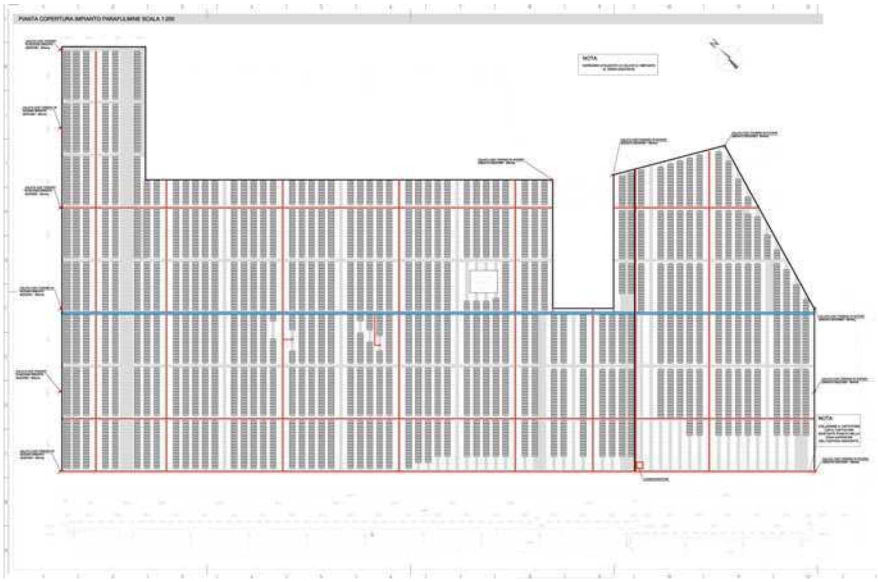


Fig. 5.28 Plan diagram detailing the layout of the 5,104 roof mounted modules (reproduced by kind permission of the MezzaCorona group)

significant solar thermal and PV installations, mounted directly on the winery buildings.

A total of 5,104 first solar thin film 75 W modules, covering an area of 4460 m^2, are mounted on the roof of the bottling line building. The existing flat roof space, however, offered no available space to mount the modules and therefore a novel solution was arrived at to mount the modules. A number of the existing roof light features were removed and their upstand structures used to provide a fixed mounting frame. Thin film technology was selected for the MezzaCorona installation based on its lower energy cost to produce, cost equivalence to crystalline modules, reduced geographical restrictions due to quality of radiation (particularly diffuse light) and ease of recycling (90% by module weight and 95% of semiconductor material). Figure 5.28 illustrates the roof layout and Fig. 5.29 shows the final installation.

The entire PV generator is connected to two Aurora Power-one 200 kW inverters, located inside the building, before feeding into the building grid via an in-line transformer. Figure 5.30 shows the inverter installation.

At a total cost of €1.5 million the installation, completed on 14th October 2010, is rated at 382.8 kWp and is predicted to produce nearly 440,000 kWh/year (approximately 10% of the building's annual requirement). The MezzaCorona winery is tied into a 20 year guaranteed Feed in Tariff of €0.399/kWh which will give an approximate payback of 9.5 years.

The facility also has 288 flat plate collectors, covering 560 m^2, mounted on the roof of the process building, providing hot water for washing and sterilisation

Fig. 5.29 Aerial view of the 382.8 kWp photovoltaic installation (reproduced by kind permission of the MezzaCorona group)

Fig. 5.30 The two Aurora 200 kW inverters

Fig. 5.31 Aerial view of the new solar thermal installation

requirements. Figure 5.31 presents an aerial view of the new facility and solar thermal installation. It is hoped that the new installation will offset a significant proportion of the facility's hot water demand, currently met by two natural gas boilers capable of delivering almost 3,350 MJ of thermal output each.

Fig. 5.32 The futuristic entrance into the Torres winemaking facility, boasting modern quality control and laboratory analysis

5.3.1.3 Case Study Torres, Vilafranca del Penedès, Spain

Located just outside the town of Vilafranca del Penedès, the Torres family have been making wine in this region of Catalonia since the seventeenth century, although it wasn't until 1870 that Don Jamie Torres created the famous house of torres. Today the family operates from its modern state-of-the-art winery, set in their extensive vineyards in the DO region of Penedès. In addition to their other vineyard and winery holdings spanning Spain and the new world, Torres is Spain's largest producer of DO wines under its own label. The current Bodegas Torres is one of the largest wine production facilities in Spain (and one of the largest red wine vinification facilities in Europe) producing 60 million bottles/year, exporting to more than 140 countries. The winery offers a range of wines, both in terms of styles (still red, white and rose, sparkling wine and sweet dessert) and grape varieties. The diversity of their vineyards means they are able to grow mid European varieties from their hillside vineyards to muscat style wines at the coastal vineyards. This diversity (coupled with large volumes) has implications back at the winery and requires that it is equipped with the most advanced, effective winemaking systems to deal with the specific needs of each wine. The rotational red wine vinification facility is just one example of this ultra modern wine producing facility. The winery welcomed more than 125,000 visitors last year, all keen to view the futuristic winemaking facility and sample some of their award winning wine (Fig. 5.32).

The Torres family have always been at the forefront of innovation and development in the winemaking industry. Today's generation is no different and they have been keen to invest in the latest winemaking technologies, utilise new concepts or practice in winegrowing and production or conduct their own ground breaking research on topics as varied as the implications of climate change on their vineyards to advanced algae CO_2 sequestration and fuel production development (Fig. 5.33). A large roof mounted solar PV installation, coupled with smaller power and thermal installations, is central to this philosophy and indicates the depth of commitment of the company in promoting a sustainable future.

Active solar energy capture has always played a part in the Torres winery. In years past traditional winemaking utilised large blackened glass jars filled with

Fig. 5.33 Experimental reactor facility for CO_2 capture and algae production

Fig. 5.34 The art of the solares—traditional old style solar capture and vinification processes

a young wine and left out in the hot sunshine to bake. Today, these jars are still used but for decorative purposes only and they can be seen on the sand covered cellar roof (*note* the white sand is used to reflect incident solar radiation during the summer months, thereby reducing solar gain to the storage spaces below (Fig. 5.34)). Torres still recognise the important part that the sun has to play in the winemaking process, this time however the winery has invested in the modern equivalent, solar PV and solar thermal collectors.

Completed in 2008, the 2,592 SunTech (260 W) polycrystalline modules cover an area of 12,000 m^2 of the storage and distribution warehouse roof (Fig. 5.35). The modules are arranged in 144 strings with 18 modules per string. The PV installation is connected to two Siemens Solar 350 kW inverters, located indoors, directly below in the warehouse building (Fig. 5.36). The power is generated at 400 V and is immediately transformed up to 25 kV where it is exported directly to the grid via a dedicated interconnector (Fig. 5.37).

Approximately 900,000 kWh/year is exported (around 11% of the total winery power demand) into the local authority's grid. Torres supplies the electricity

Fig. 5.35 The 673.92 kWp roof mounted photovoltaic installation

Fig. 5.36 The two indoor located Siemens Solar 350 kW inverters, complete with dedicated mechanical ventilation

through a guaranteed FIT set at €0.45/kWh, but buys electricity back at €0.11/kWh. This equates to an approximate payback of 8–10 years on a solar project that was completely funded through the personal finance of Torres.

In addition to the 673.92 kWp roof mounted photovoltaic installation, there are a number of other solar installations located at various buildings throughout the facility. A small double axis tracking PV installation powers the lighting systems of the cellar building and a roof mounted flat plate collector system, covering more than 100 m^2, provides energy to heat the water used in the bottling washing processes at the site.

Fig. 5.37 Grid interconnection from the Torres winery PV installation

5.3.1.4 Case Study Peitler, Styria, Austria

The Peitler winery at Leutschach, Styria, is a small family run winery producing 30,000 l/year of high-quality wines which come from their 5.5 ha of vineyards located in South Eastern Austria. The winemaking facility consists of the main winery building, housing the wine production facilities, and the family home which is used primarily for hospitality and administration. The winery and family home have an overall heating load of 50 kW used for space heating, process heat (fermentation control of the wine production) and domestic hot water preparation. The cooling load is 10 kW and is used for chilled water for fermentation control and cooling and dehumidification of the wine bottle store.

The facility is almost totally self sufficient in energy thanks to the solar thermal and bio-mass systems installed in the winery. The system, which is a demonstration scheme funded through PolySMART and managed by Joanneum Research, Graz [11], is the first demonstration of combined heating, cooling, power (CHCP) technology in a commercial winery. Figure 5.38 shows the winery with the 100.8 m^2 roof mounted solar thermal collector.

The complete system consists of 100.8 m^2 of roof mounted flat plate collectors, a micro-CHP system comprising a 50 kWth wood chip furnace connected to a 3 kWel Stirling engine prototype. Cooling is provided by a novel NH_3/H_2O absorption refrigeration unit, developed by Pink GmbH, with two evaporators; chilled water production and direct air cooling for the wine bottle store. All the

Fig. 5.38 The Peitler winery and solar installation (reproduced by kind permission of Peitler winery)

produced heat (solar, wood chip furnace, Stirling waste heat) is transferred into a 4.8 m^3 buffer store, whilst the chilled water is stored in a 0.5 m^3 buffer vessel. The facility is schematically demonstrated in Fig. 5.39.

Over a 1 year monitoring period (Dec 2008 to Nov 2009) the combined system was supplied with 91,463 kWh equivalent (55,020 kWh from the solar and biomass, 31,493 kWh from the backup fuel and 4,950 kWh of electricity from the utility) and produced 53,339 kWh of heating, 5,020 kWh of cooling and almost 5 kWh of electricity. Figures 5.40 and 5.41 show the bio-mass system and absorption refrigeration unit, respectively.

On comparison with a conventional compression cooling system, a total of 4 kW of electrical power would be required to achieve the 10 kW of cooling, whereas the experiences of the absorption refrigeration system installed at the Peitler winery has shown that only 0.25 kW of electrical power is needed for the same cooling. The heat demand and the heat flow however increases but this is not a significant issue as the heat is produced from the solar and bio-mass which is also used in meeting the hot water and space heating demands. Comparing both systems on purely economic terms (excluding the Stirling engine) the investment cost for the absorption refrigeration system was €47,150 opposed to only €33,314 for a conventional compression cooling system. However, electrical operating costs for the absorption system were calculated to be only 17.6% of that required by the conventional system and, along with reduced maintenance costs, made it much more economical to operate.

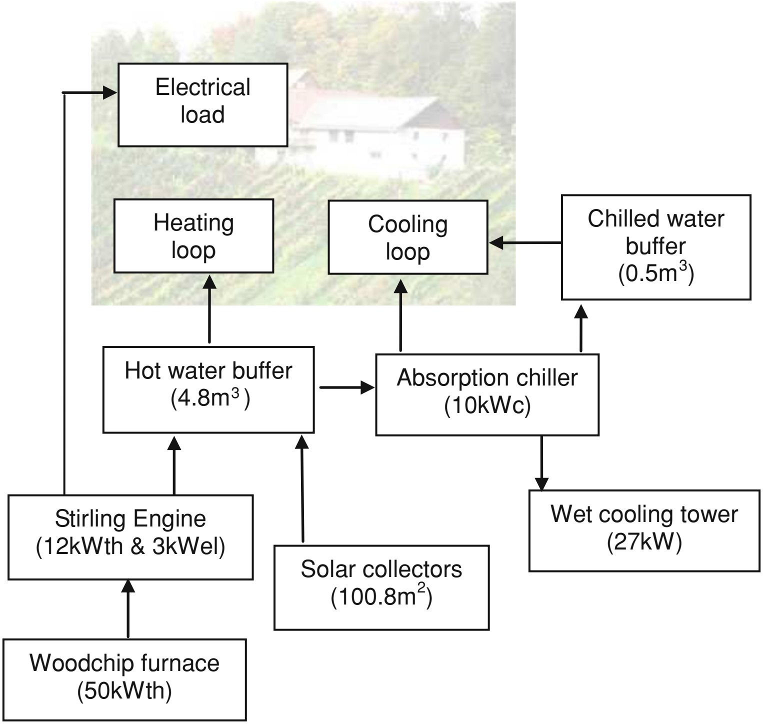


Fig. 5.39 Schematic layout of the solar augmented tri-generation

Fig. 5.40 The 50 kWth wood chip furnace connected to a 3 kWel Stirling engine prototype

5.3.1.5 Case Study Weingut Pfaffmann, Impflingen, Germany

The first mention 'Pfaffmänner' (men of the Pfaffen) in the Landau/Pfalz region and a connection with wine comes in 1520. More recently, modern wine

Fig. 5.41 The 10 kWc NH_3/H_2O absorption refrigeration unit

Fig. 5.42 Entrance to Weingut Pfaffmann

production by the Pfaffmann family can be traced back to 1964 when Gerd and Gertrud Pfaffman moved from the small village winery in Impflingen to a more substantial facility at Gertrudenhof on the outskirts of the village. In 1986 Gerd's son, Gerd Walter Pfaffman, took over the winery and through his drive and determination the winery has continually expanded and has adopted a more sustainable approach to winemaking, which is very much in keeping with their philosophy 'We winegrowers live with and on nature' (Fig. 5.42).

Nestled in the beautiful rolling hills of the famous Pfalz region of Germany, Weingut Pfaffmann is surrounded by 35 ha of their vineyards (Fig. 5.43). Producing approximately 350,000 l of wine/year, the winery offers a wide range of traditional still red and white, sparkling and dessert wines. On arrival at the winery

Fig. 5.43 Aerial view of Weingut Pfaffmann and vineyards (reproduced by kind permission of Weingut Pfaffmann)

tasting room, you are greeted by a warm family welcome and an almost unconscious statement of the family's desire for real sustainable action. During the depths of a German winter, grubbed up vines are given a secondary lease of life (and use to the winery), if only temporarily, as they are used in a small wood stove located in the vinotech (Fig. 5.44).

A solar facility forms the centre piece in the winery's sustainability plan. The installation consists of 4,227 first solar modules (75 W) mounted on the roof of the winery, covering an area of approximately 3,500 m^2. The roof features various low sloping surfaces, giving rise to 45 different arrays, facing in several directions. The complete installation is rated at 317 kWp DC, connected to 45 inverters (Solamax and Fronius), one for each array. Figure 5.45 depicts the installation mounted on the roof of the winery and Fig. 5.46 shows one of the internal wall mounted inverter stations located throughout the winery.

The PV system was installed in two phases. The first phase was installed in 2004 at a cost of €135,000 for a 30 kWp DC system which gave an average installed cost of €4,500/kWp. The second phase, installed in 2009, cost €783,510. This system was rated at 287 kWp giving an average installed cost of €2,730/kWp. Due to the increase in size, an additional €109,000 was needed to cover the cost of the new interconnection transmission line and transformer (Fig. 5.47). The complete installation cost was €1,027,510.

The winery operates on a generous feed in tariff structure, feeding an average of 291,640 kWh/year indirectly into the local electricity supply authority's grid (Fig. 5.48), whilst paying for the winery's typical annual electricity requirement of 50,000 kWhs at 22.5 cents/kWh for the grid. As the PV installations were installed 5 years apart, 2 FITs are in operation; €0.54 is paid per kWh for the 30 kWp installation which at 920 kWh/kWp equates to €14,904 annually and €0.41/kWh is paid for the 287 kWp installation which again at 920 kWh/kWp equates to €108,256/year. This gives Weingut Pfaffmann an annual income of €123,160 giving a basic payback of 8.4 years.

Whilst the winery has on the whole been very happy with the performance of the installation, there have been a number of issues worth comment. The initial 30 kWp DC installation, using Antech modules, went operational in December 2004. Four months later, however, in April 2005, the modules failed. This coincided with a

Fig. 5.44 Unconscious sustainability in action

Fig. 5.45 The 317 kWp DC PV installation mounted on the roof of the winery (reproduced by kind permission of Weingut Pfaffmann)

Fig. 5.46 The internally mounted inverter station

Fig. 5.47 The three phase 415 V–20 kV transformer for transmission to the point of grid-interconnection

Fig. 5.48 Incoming and outgoing electricity metres, remotely monitored by the local power supply company

significant increase in the seasonal solar input. Due to legal issues, the modules were not replaced until December 2006. Another interesting issue relates to the washing of the PV modules. Due to the high chalk content of the local water supply, the modules are washed using collected rainwater. Given the size and spread of the PV installation, the winery is now seriously considering purchasing a robotic module washing unit, although costs in excess of €50,000 are quite large and difficult to justify.

Fig. 5.49 The Hagafen winery and PV roof installation

5.3.2 Solar Case Studies in the New World

5.3.2.1 Case Study Hagafen Cellars, Oak Knoll, Napa Valley, California

Hagafen Cellars is located in the Napa Valley, in the heart of California's premier wine producing region, in the Oak Knoll District, Napa's newest and most exciting AVA. The well drained soil is ideal for the growth and production of ripe and rich, intensely fruity small lot estate bottled wines. Owned and operated by Irit and Ernie Weir, the winery was founded in 1979 and the first commercially released vintage was harvested in 1980. In the ensuing years, they have grown from a small partnership into a well established wine company whose wines are distributed throughout North America and overseas and on occasions their wines have been served at the White House to visiting foreign dignitaries (Fig. 5.49).

The 36.5 kW DC photovoltaic installation comprises 170 SunPower SPR-215 215Wp modules mounted on the roof of the winery. The modules are facing southwest at an incline of 25°. As the roof space available for the PV installation was small, the SPR-215 modules with an operating efficiency of at least 20%, maximised power generated per unit area. The PV modules were originally connected to a 30 kW Xantrex PV-30 208 inverter, however due to a tree falling on the unit, this was recently replaced with a 30 kW Satcon inverter. The typical solar input into the building is 126,127 kWh annually, producing 34.3% of the winery's total electrical requirement. Figures 5.50 and 5.51 show the annual energy inputs for the winery and inverter station, respectively.

5.3.2.2 Case Study Frogs Leap, Rutherford, California

Originally founded on a spot along Mill Creek known as the frog farm, John Williams started frog's leap in 1981 at the site of the historical Adamson Winery,

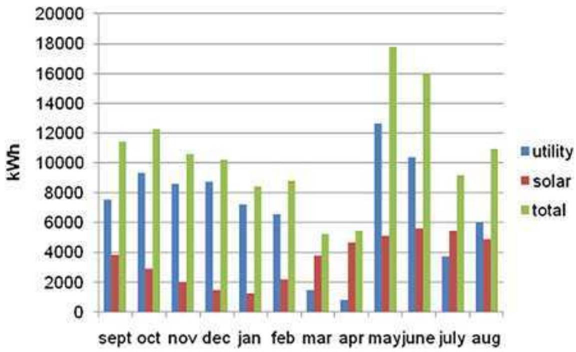


Fig. 5.50 Annual electrical energy inputs for the winery

Fig. 5.51 The new 30 kW Satcon inverter

originally built in 1884. One of the key features of the property was the historical red barn which John and his team restored to its original state in 1994 using many of the original timbers. Frog's Leap is set amongst 130 acres of vineyards in Rutherford. Using the best of Napa Valley's organically grown grapes and the most traditional winemaking techniques, frog's leap strives to produce wines that deeply reflect the soils and climate from which they emanate. Preserving the environment and stewardship of the land are core values for frog's leap. Some of the practices that demonstrate frog's leap's commitment include the use of compost and planting of cover crops to organically enrich the soil and dry farming to conserve water and reduce soil erosion. But it was not until 2004 that solar PV came to the fore (Fig. 5.52).

Fig. 5.52 The historical Red Barn at Frog's Leap

Fig. 5.53 The 178 kWp DC PV installation mounted above the leech field

The 178 kWp DC photovoltaic installation uses 1,020 sharp (175 W monocrystalline) modules facing southeast tilted at 5° angles. Covering 1/2 acre of the winery's septic leeching field, the system does not use any valuable vine growing area but yet offers a suitable site with full solar access (Fig. 5.53). The high performance modules (16.2% cell conversion efficiency), are mounted on a GroundTrac™ ground mount racking system, which was supported on 328 concrete piers (300–600 mm deep). Each panel weighs approximately 16.5 kg and has tempered, anti-reflective glass with a rust-proof aluminium frame. The installation is connected to a 225 kW Xantrex PV-225 inverter, located adjacent to the collector field (Fig. 5.54).

The annual output of frog's leap's photovoltaic system is typically 260,000 kWh, which is about 85% of the winery's requirement. John Williams believes that 85% is beneficial in that it offers an incentive to reduce the winery's electrical consumption through changing to more efficient lighting and altering the cycle times of some of the higher-use equipment, without breeching the PG&E imposed 100% ceiling. Good monitoring is essential to measure the energy dynamics. The PV system at frog's leap is monitored using the Fat Spaniel's monitoring solution. Real-time online monitoring with multiple views, SMS-based

Fig. 5.54 The 225 kW Xantrex PV-225 inverter

alerts and web based triggers for automated module washing and cooling gives management live feedback of the system performance.

The system went live on February 2005, with the installation being completed in 11 weeks, which was within the 12 week estimate. At a cost of US $1.2 million, the overall cost to frog's Leap was much less. With a 50% rebate from pacific gas and electric's self generation incentive programme worth US $600,000 and with other available tax credits and deductions, frog's leap's investment in solar power will take less than 6 years to payback.

5.3.2.3 Case Study Flora Springs, Rutherford, Napa Valley, USA

Flora Springs winery sits on 90 acres of vineyard at the base of the Mayacamas Mountains in the far Northwest corner of the Rutherford appellation, Napa Valley. Founded in 1978 and named in honour of their mother and grandmother (both flora) and natural springs that flow on the vineyard property, Flora Springs is the epitome of a family winemaking tradition. The third-generation vintners, Nat Komes and Sean Garvey, both of whom grew up at the winery, are committed to the traditions of fine winemaking, whilst maintaining and developing innovative and sustainable methods to their winemaking processes. Today, all of their wines are crafted in the solar powered nineteenth century stone winery and caves and sold in their modern tasting facility (Fig. 5.55).

The PV installation is located in the hill directly above the winery, with all round perfect solar access (Fig. 5.56). Mounted at a height of over 3 m on a lightweight galvanised sheet steel structure using horizontal purlin cross beams on vertical purlin columns (Fig. 5.57), the framework is strong enough to support the modules with design wind loading yet light enough to avoid over specification and thus cost of the structure. The 435 SunTech 170 W modules are tilted at approximately 5° due south. Rated at 74 kWp DC and covering an area of 600 m^2, the system yields approximately 100,000 kWh/year. The modules are connected to

Fig. 5.55 Blending the old with the new; the nineteenth century stone winery (*left*) and modern tasting facility (*right*)

Fig. 5.56 The elevated PV structure provides ample covered space for storage of vineyard equipment and materials

Fig. 5.57 Detail of the underside of the modules and mounting frame

two PVP 30 kW inverters (Fig. 5.58), located under the north-eastern corner of the raised structure, realising a significant level of shading. The elevated PV structure provides ample covered space for storage of vineyard equipment and materials and the exposed overhead position of the modules allows for all over air movement around, providing increased access to surface cooling.

Fig. 5.58 The 2 PVP 30 kW inverters, located under the north-eastern corner of the raised structure

Solar power is just one part of Flora Springs' sustainable activities. Throughout their 650 acres, across 5 appellations, sustainable farming is practiced. It is part of the family tradition…. 'good stewardship of the land and be a good neighbour'. The choice to go solar was not difficult and fits perfectly with the ethos of residing harmoniously within the land and community.

5.3.2.4 Case Study Jacuzzi, Carneros, Sonoma Valley, California

Jacuzzi family vineyard winery is set on 190 acres of vineyard in the Carneros region of Sonoma, California. The beautiful 1700 m^2 rustic-Italian stone structure was inspired by the Jacuzzi family home in Udine, Italy. Owned and operated by descendants of the Jacuzzi family of pump and spa fame, the winery produces 18 different wines, all under the Jacuzzi Family label. Jacuzzi Family Vineyards is an example of a company that has made a commitment to producing high-quality wine through environmentally conscious business and sustainable farming practices (Fig. 5.59).

The 124 kWp DC, 103 kWp AC photovoltaic installation comprises 748 mitsubishi electric 165 Wp modules mounted in 3 different configurations, giving the system a unique status in winemaking facility installations. A fixed ground mounted structure, a fixed pole mounted structure and a ground mounted, single axis tracker were all employed due to limited ground space. The fixed portion of the solar system, 61.7 kWp, provides nearly 100% of the electricity for the water well and fire pumps and comprises the fixed ground mounted system and single pole mounted system. Both systems face directly south and the pole mounting ensures the modules are above any tree shading at the site boundaries. The remaining 61.7 kWp portion is connected to a single axis tracker, allowing the solar modules to follow the sun, thus generating an estimated 15–20% more

Fig. 5.59 The winery and PV installation (reproduced by kind permission of Jacuzzi)

Fig. 5.60 All three PV mounting configurations (*left*) pole mounted (*foreground*) fixed ground mounting (*background*) single axis tracking

Fig. 5.61 View due south with inverters (*right*)

electricity for the winery than if the modules were in a fixed position. This system provides a significant portion of the electricity for the winery building. Each PV system is connected to one of two 50 kW Satcon inverters, producing an estimated 185,130 kWh annually, representing 53% of the facility's annual electrical requirement (Figs. 5.60, 5.61, 5.62).

To date, the winery has had no significant problems with the installation and the entire solar system is expected to pay for itself in 6 years. By taking advantage of the federal tax credit, California state rebates, and accelerated depreciation, the

Fig. 5.62 Tracking system motor and guides

Fig. 5.63 North facing view of the Domaine Carneros château

winery was able to reduce the total system cost by nearly 75%, making the whole project a very worthwhile endeavour.

5.3.2.5 Case Study Domaine Carneros Estate, Carneros, California

The Domaine Carneros estate is situated in the Carneros appellation at the bottom of the Napa Valley. The region is characterised by a long, moderately cool growing season tempered by the maritime breezes and lingering fog of the San Pablo Bay just to the west, perfect for growing the grapes for the super-premium sparkling wine (traditional *methode champenoise*) produced by the Domaine Carneros estate. Domaine Carneros also produces quality white and red still wines and, together with the sparkling wines, produce on average over 80,000 cases/year.

The winemaking process is housed in two buildings; the spectacular Château and the modern Pinot noir facility. The Domaine Carneros château is a landmark of the carneros region. Completed in 1989, the classic eighteenth century château-style building was architecturally inspired by the historical Taittinger-owned Château de la Marquetterie in Champagne. Situated atop a knoll surrounded by its 100 acres of vineyards, the chateau offers exquisite views of endless vineyard-covered hills (Fig. 5.63). The Pinot noir facility sits just behind the main château and was styled after a French carriage house. When completed in 2003, this

Fig. 5.64 Domaine Carneros château and Pinot noir facility (reproduced by kind permission of Domaine Carneros)

Fig. 5.65 Photovoltaic installation (phases 1 and 2)

state-of-the-art facility had the largest solar collection system of any winery in the world (Fig. 5.64).

There are two separate PV installations (phases one and two) installed on the buildings at Domaine Carneros. The first system was installed in 2003 onto the Pinot Noir facility roof, rated at 120.4 kWp DC consisting of 688 modules, arranged into 86 strings. The second system was installed in 2006 onto both the Pinot Noir facility roof and Chateau roof, rated at 76.4 kWp DC consisting of 392 modules, arranged into 49 strings. The total installation covers an area of 1,275 m^2. Figure 5.65 shows the PV installation as viewed from the roof of the chateau building.

Both arrays were installed using the Powerguard® photovoltaic roofing system, incorporating Sanyo HIP-195BA3 tiles. Designed and installed by Powerlight (now Sunpower), Powerguard® is a lightweight building-integrated photovoltaic roofing system that was installed over the existing waterproof roof membrane. The PV tiles are backed with insulating polystyrene foam and connected together with interlocking tongue-and groove side surfaces. Around the perimeter of each array, RT curbs are fitted to resist wind uplifts whilst providing ballast that ensure installation without the need for roof penetration. In addition to generating electricity, this novel BIPV installation provides thermal insulation (U value = 0.16 W/m^2 K or US R35), helping to reduce the building's cooling load and protecting the roof membrane from damaging UV rays and thermal degradation (Fig. 5.66).

Fig. 5.66 Detail of Powerguard® lightweight building-integrated PV roofing system

Fig. 5.67 Photovoltaic installation inverter unit

Each array is connected to a dedicated 100 kVa Xantrex inverter (Fig. 5.67) which is connected to the winery's main switch board panel, with the option of feeding into the electrical supply authority's grid via a net metering connection. Figure 5.68 details the schematic electrical configuration for the entire PV installation.

Figure 5.69 details the electrical supply and demand profiles for Domaine Carneros from October 2007 to date. Overall, the solar facility contributes up to 26.8% of the winery's total electrical load.

Apart from the novel building-integrated photovoltaic roofing system, Domaine Carneros has invested in many other energy saving features within the winery. The Pinot noir facility incorporates a SunPipe® daylighting system. Traditional skylights allow unfiltered light through large openings in the roof resulting in a solar heat gain within the space below. The sun pipes use only 10% of the area used by a skylight, maintaining a larger insulated roof area. So in addition to a reduced electrical lighting load, they reduce HVAC loads by introducing less solar heat gain whilst creating a roof feature with a higher insulating performance. Figure 5.70 depicts the external and internal features of the daylighting system in the Pinot Noir facility.

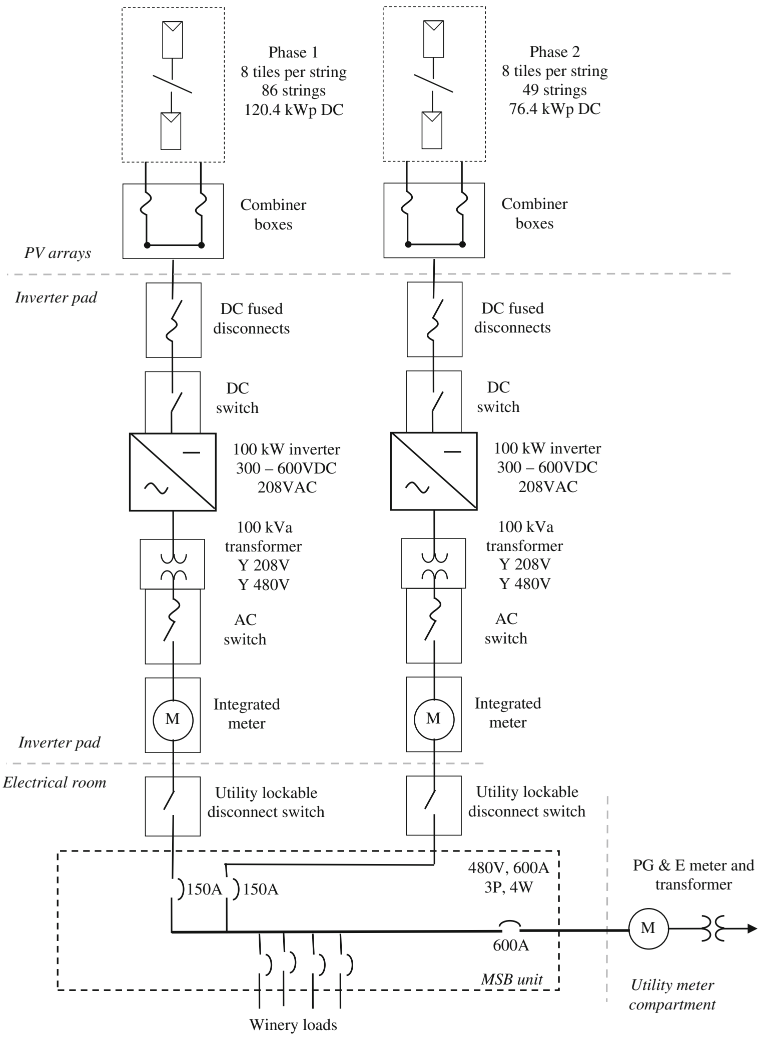


Fig. 5.68 Schematic detail of the PV installation

5.3.2.6 Case Study Far Niente, Oakville, California

Far Niente was founded in 1885 by John Benson, a forty-niner of the California gold rush and uncle of the famous American impressionist painter, Winslow Homer. Benson hired the architect Hamden McIntyre, creator of the former Christian brothers winery, to design the building. Constructed against a hillside in western Oakville, Far Niente functioned as a gravity flow winery, gently moving the grapes through each stage of production (Fig. 5.71).

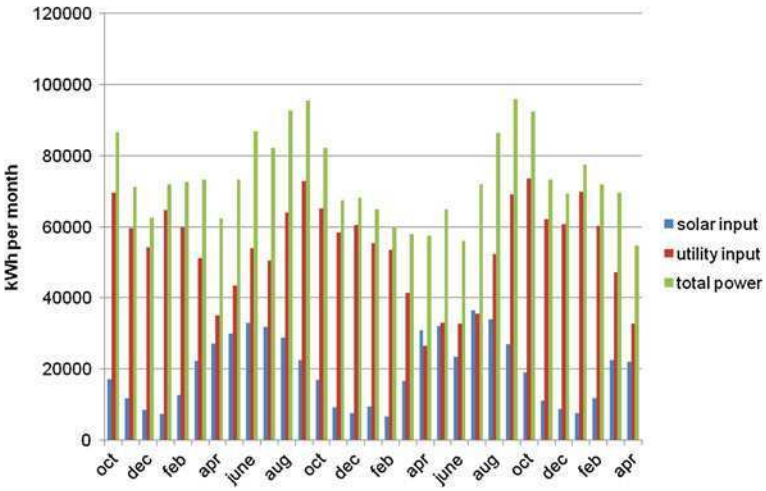


Fig. 5.69 Electrical supply and demand profile for Domaine Carneros (October 2007 to April 2010)

Fig. 5.70 External and internal images of the daylighting system in the Pinot Noir facility

Fig. 5.71 Far Niente winery (reproduced by kind permission of Far Niente)

Fig. 5.72 Far Niente ….."without a care"

The winery prospered until the onset of Prohibition in 1919 when it was abandoned and left to fall into disrepair. Sixty years later, in 1979, Gil Nickel purchased the winery and adjacent vineyard and began a 3 year restoration of the property. During restoration the original name, Far Niente, from an Italian phrase that romantically translated means "without a care," was found carved in stone on the front of the building where it remains to this day. A wooden sign dating to the beginning of the twentieth century was found in a local barn and now hangs prominently in the winery's Great Hall (Fig. 5.72).

Today, Far Niente, follows an integrated program of sustainable measures affecting vineyard, winery and day-to-day business practices. Their status as world leaders in sustainable wine production and champions of the solar winery is clearly identifiable through their floating solar PV installation. The large scale grid-connected PV installation is the first of its kind in the world. Completed in April 2008, the "Floatovoltaic" System is capable of supplying the winery's entire annual electrical requirement.

The installation consists of 2296 modules (sharp 208) with 994 of the modules mounted on pontoons floating on the irrigation pond in Far Niente's Martin Stelling Vineyard, representing 43% of the system coverage. The remaining 1,302 modules are mounted on land adjacent to the pond (Fig. 5.73). In the wine producing region of the Napa Valley, viable vineyard growing area is very valuable. The use of a floating PV system offsets land that would otherwise be used for PV mounting. In Far Niente's case, 1.2 acres was used for land mounted modules but 0.75 acres offset by the pond array meant that they saved the equivalent of US $150,000 in revenue of bottled Cabernet Sauvignon being lost annually. The completed installation was rated at 478 kWp DC converting to 400 kWp AC through the 500 kW Satcon inverter (Fig. 5.74).

At a cost of US $4.2 million, the installation was not cheap. However, through the self generation incentive programme (SGIP), the winery received a US $2.80/ DC Watt cash rebate from PG&E. Along with a 30% federal tax credit and accelerated 5 year depreciation, this creative financing package and novel lease-back agreement made the project more feasible. Bank of America Leasing and Capital LLC purchased Far Niente's solar installation, which the winery leases and

Fig. 5.73 Aerial view of the pond and land mounted PV array (reproduced by kind permission of Far Niente)

Fig. 5.74 500 kW Satcon inverter, isolation transformer and 480 V–5 kV transformer for transmission to the point of grid-interconnection

has a buyback option after 7 years. Together with a non-floating PV installation, located at Far Niente's sister winery, Nickel and Nickel, the estimated base cost for the system is around US $7.30/DC Watt. To date, the solar installation will pay for itself in 13–17 years.

Of course there are several complexities involved in installing a floating PV array, a strong foundation being the most obvious, coupled with the constant water/electrical hazard. At Far Niente these problems have been overcome through mounting the PVs on pontoons made from two concentric plastic, ribbed drain pipes, sealed with the inner pipe filled with expanded polyurethane foam (Fig. 5.75). A total of 130 pontoons were used, supporting approximately 8 PV modules each. The pontoons

Fig. 5.75 Floating array and pontoon detail

Fig. 5.76 Photovoltaic installation mooring assembly

were designed to rise and fall with the level of the pond and to touch bottom should all the water be pumped out for frost protection or irrigation. Movement of the PVs would have been a particular issue, either from moving from optimal collection position or damage resulting from wind loading, required that the PVs and pontoons were securely fixed to the pond banking. Figure 5.76 details the mooring of the

Fig. 5.77 String cabling from the PVs

support pontoons via rigid cabling fixed firmly to embedded concrete columns. In addition, water and electricity generally do not mix, therefore to ensure safe connection to the land based inverter, all power cabling was marine grade insulated. Figure 5.77 details string cabling from the PVs.

Apart from the financial benefit of offsetting the use of precious real estate, the PV covered pond has some other important benefits. The shading effect of the PVs, thereby reducing solar energy incident on and thus absorbed by the pond, lowers the gain in pond water temperature and reduces the rate of surface evaporation from the pond, maintaining a valuable resource for irrigation and frost protection. From a solar PV operating perspective, the locality of the modules to the body of water had a cooling effect and PV panel temperatures were up to 2.8°C less than the land based modules.

One other feature of note at the Far Niente facility is the energy saving wine caves. In 1980, one year after Far Niente was purchased by Gil Nickel, a small 18 m wine cave in the hill behind the winery was commissioned, the first wine caves constructed in North America since the turn of the century. Almost 10 years after the first excavation the wine caves were expanded to 1400 m^2. A second phase in 1995 added an additional 1200 m^2 and a third phase in 2001 brought the total cave area to 3700 m^2. The caves are beautifully designed and integrated fully in keeping with the aesthetics of the winery. Apart from beautiful surroundings for the aging wine, many practical benefits can be attributed to storing and aging wine underground. A constant temperature of 15°C, accompanied by natural humidity,

Fig. 5.78 Far Niente's cave complex

contributes to low evaporation in a consistent environment. From an energy perspective, this passive cooling imparted through wine caves can have a significant impact in reducing storage cooling loads. Far Niente's caves currently house approximately 2,500 French oak barrels, as shown in Fig. 5.78.

One consequence of being fully sufficient in solar generated electricity is that Far Niente has been able to express their winery building through an award lighting scheme. The landscape lighting won the 1997 general electric lighting award, over the Museum of Contemporary Art, Chicago; The Guggenheim Museum, Spain; Bloomingdales, New York city and the FDR Memorial, Washington D.C. Although not totally in keeping with a sustainable agenda, the lighting requirement is more than offset by the PV installation. Figure 5.79 beautifully captures the Far Niente building at night.

5.3.2.7 Case Study Saintsbury, Carneros, Napa Valley, USA

Founded in 1981, Saintsbury winery was named after George Saintsbury, a British wine connoisseur. The vineyards and winery are located in the cooler carneros region of the Napa and Sonoma Valleys, bordered by the San Pablo Bay. Because of this geographical position, Saintsbury has the ideal climatic conditions necessary for producing great pinot Noir and Chardonnay. In addition, the typical clay-loam soils of carneros also helps create near ideal conditions for pinot Noir and Chardonnay cultivation. The same awareness that allows Saintsbury to produce outstanding wines is also reflected in their enthusiasm and contribution to

Fig. 5.79 Far Niente by night (reproduced by kind permission of Far Niente)

Fig. 5.80 The Saintsbury winery, with PV carport to the *right* in the background

sustainable wine production, realised in part through their new carport PV installation (Fig. 5.80).

The PV installation at Saintsbury comprises of 560 Sanyo 200 W modules mounted on a car port structure (Fig. 5.81), covering an area of 650 m^2 and connected to one 100 kW Xantrex PV100S-208 inverter (Fig. 5.82). The inverter is located directly under the carport at the north-eastern corner, thus taking full advantage of the cooling provided through PV shading. The complete system is rated at 112 kWp DC and yields 162,086 kWh/year.

Fig. 5.81 The Saintsbury winery PV carport

Fig. 5.82 The 100 kW Xantrex PV100S-208 inverter

The concept of a carport PV structure was based on a number of factors namely that the winery building was not structurally strong enough and was not oriented in the correct direction and space around the winery both for vehicles and winery activities was scarce. Fortunately, a small, old random varietal vineyard block existed just south of the winery. The availability of this space and a need for car parking meant that a solar PV carport would provide shade for vehicles (Fig. 5.83) and covered storage space for winery/vineyard equipment, whilst the high mounting location would provide a significant level of module security. The overhead mounting position also allows for all over air movement around the modules, providing increased access to surface cooling.

After some initial teething problems, the system has been very successful in providing most of the winery's electricity and offsetting all of the winery's electrical costs. One particular problem, however, associated with the location of the PV structure was the presence of PG&E's 240 kVA overhead power lines. Due to

Fig. 5.83 Shading under PV carport

the presence of the overhead power lines, the winery had to consider an easement allowance to ensure that the utility provider had sufficient access. Following a number of discussions with the installer, the maximum height of the structure was reduced and the problem resolved. Figure 5.84 depicts the proximity of the power lines to the PV carport structure.

5.3.2.8 Case Study Miner, Oakville, Napa Valley, California

Miner Family Vineyards is a dynamic family owned winery tucked into the eastern hills of the Oakville appellation, in the heart of the Napa Valley. Founded in 1998 by Dave and Emily Miner along with his parents Ed and Norma, Miner is defined first and foremost by a sensational portfolio of wines consistently characterised by and committed to individualistic style and uncommon quality.

The 1850 m^2 hillside winery, first designed as a custom crush facility, includes the crushing facility, fermentation room, barrel aging room, bottling room, public tasting room, laboratory and offices and incorporates an extensive cave storage facility, located behind the winery, above which the ground mounted PV installation is located.

The 14 arrays of the 378 kWp DC, 323 kWp AC system are integrated into the steep southwest facing slope at a tilt of 35°. A total of 1,750 sharp 216 W PV modules are connected to the advanced energy solaron 333 kW inverter. Due to the presence of overhead power lines, the arrays had to be designed in such a way to provide a 10 m wide easement to allow the utility provider sufficient access,

Fig. 5.84 The PG&E's 240 kVA overhead power lines in relation to the PV carport

ensuring that the PV installation was spread over a larger area of the hillside. The impact of the easement can be seen in Fig. 5.85. Given the prominence and proximity of the PV installation to a main scenic roadway, the larger installation area (in part) resulted in a 1 year long zoning and permitting approval from the County of Napa (Figs. 5.86, 5.87).

Commissioned in January 2009, monitoring began in April 2009. Figure 5.88 details the monthly electrical production from the PV installation since April 2009. In the past year, the installation has produced 562,950 kWh, producing 108% of its predicted forecast at the time of installation and supplying the winery with almost 92% of the building's total electrical load.

Fig. 5.85 Fixed PV installation located into the hillside adjacent to the winery (reproduced by kind permission of Sunlight Electric, LLC)

Fig. 5.86 Image of one of the hillside arrays

5.3.2.9 Case Study Ridge Vineyards, Lytton Springs, Sonoma County, California, USA

Although Ridge vineyards can trace their history back to 1885 when Osea Perrone, a physician and prominent member of the San Francisco Italian community, bought 180 acres near the top of Monte Bello Ridge, it was not until 1991 that the

Fig. 5.87 The Advanced Energy Solaron 333 kW inverter

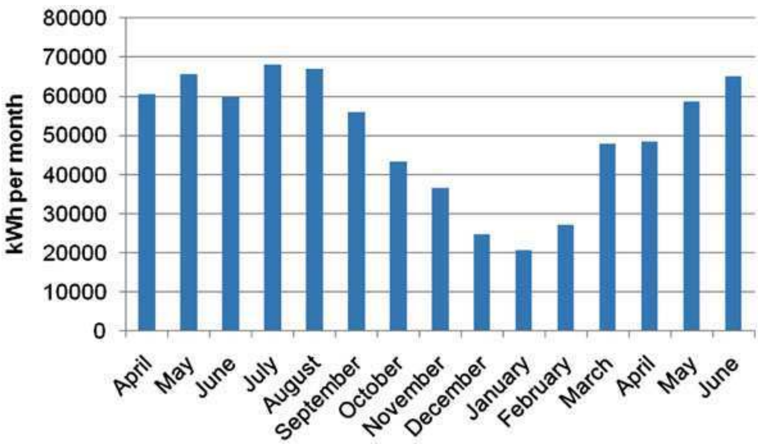


Fig. 5.88 Monthly electrical production from the PV installation since April 2009

Lytton Springs vineyard and winery became part of the Ridge estate. Surrounded by beautiful 115 year-old vines, the recently renovated Lytton Springs tasting room and winery (Fig. 5.89) is one of the most unique wineries in the Sonoma County wine country. A natural extension of Ridge's commitment to sustainable vineyard and winery practices, the facility is an exemplar of modern winery design.

Fig. 5.89 Lytton Springs tasting room and winery

The renovated Lytton Springs facility is one of the most environmentally sensitive wineries in California. Many wineries are designed with winery operation and functionality uppermost in the designer's process of thought. However, this concept, whilst producing environmentally conscious winery buildings, does not consider the embodied energy and sustainability of the construction materials. The Ridge winery differs in that a full life cycle approach was adopted from the beginning and building materials were sought that would consider the total energy footprint of the building. After much research, a revolutionary straw bale structure was agreed upon to be the best option and when the winery was completed in 2004 it was the largest commercial straw bale building in the US.

In order to satisfy building codes in earthquake prone California, the building is a post and beam structure, using recycled timber where possible, with straw bales providing a highly insulating wall "infill". Keeping the environmental theme, the straw bales are sourced locally from the rice industry in California's Central Valley. Rice straw is high in silica, making it indigestible and very slow to decompose. Rice farmers traditionally burnt the straw after each harvest, but due to air pollution legislation, this practice is now forbidden. The straw bale structure is covered with a wire mesh and earthen plaster (including chopped rice straw) which was applied to all exterior walls and some of the interior walls. This structure, whilst providing excellent thermal mass, also creates a permeable skin, permitting the walls to "breathe". Large overhangs provide solar shading and high ceilings are designed to create stack effect coupled with night-time purge ventilation to create a space that is comfortable for the occupants but complimentary to wine production and as a result no air conditioning is necessary except as a back-up in the barrel storage room.

Initially designed in a sloped east/west orientation, the winery roof was changed to a north/south orientation, presenting an extensive south facing structure on which to mount a photovoltaic installation. This is an interesting example of how

Fig. 5.90 View of the PV installation (reproduced with kind permission of Ridge Winery)

an active solar augmentation can influence the physical layout and external appearance of a new winery. A total of 400 (Power light) modules were mounted on the roof of the Ridge winery. Due to the roof design, the PV generator was connected in 2 differently sloped arrays; 35° and 17° tilt. The complete installation is rated at 65 kWp DC. Figure 5.90 shows the building with the installed PV modules.

As seen from Fig. 5.90, the combined DC cable enters the winery from the east-side of the building and traverses the underside of the roof to be connected to two 30 kW Xantrex inverters, internally mounted at the west-side of the winery. The reason for this circuitous route is unclear but it is envisaged that the decision was based on an architectural issue. The extended DC cable not only results in increased installation cost but also results in increased power transmission losses. Figures 5.91 and 5.92 detail the DC cable/conduit path on the underside of the roof and the Xantrex inverter station, respectively.

The PV installation is connected to the building grid, and via a net metre electricity can be exported or imported depending upon the winery demand. The PV facility supplies approximately 85,000 kWh/year, providing 75–85% of the winery's electricity needs over the course of a year.

5.3.2.10 Sonoma Wine Company, Graton, Sonoma County, California, USA

The Sonoma Wine Company, whilst also producing wine under its own label, is one of the largest wine contract service providers in Northern California. Sonoma Wine Company operates six facilities throughout California with the Graton facility in Sonoma County, at over 16,700 m^2, being the largest, offering bottling, wine processing and storage services to the local winemaking community. The company has long been recognised for its efforts in tackling GHG emissions and promoting sustainable practices and has implemented many energy efficiency and water conservation measures at the Graton site. The latest addition has been the

Fig. 5.91 View of the extended DC cable/conduit path on the underside of the roof

Fig. 5.92 The 2 30 kW Xantrex inverters and ancillary equipment

installation of a unique solar co-generation system. The solar installation at the Sonoma wine company's Graton facility is not owned by the winery but rather is operated by Cogenra Solar through a heat and power purchase agreement (HPPA).

Located in the town of Mountain view, Cogenra Solar are a local Californian solar provider, offering combined solar hot water and power generation through their innovative PV/thermal (PVT) collector. At the Sonoma wine company, Cogenra Solar fully financed the design, fabrication and installation of the entire solar system. Under the HPPA, Cogenra Solar operates and maintains the system, whilst providing thermal energy and power to the winery at a cost lower than local utility rates.

Fig. 5.93 Sonoma wine company

Fig. 5.94 The front row, consisting of three Cogenra SunBase^{TM} concentrating collectors

The Sonoma wine company benefits by having a visual solar profile and lower energy costs, all with a minimal up-front capital expenditure. (Fig. 5.93).

The ground mounted single axis tracking PVT solar facility is the first of its kind installed in any winery in California. Developed by Cogenra Solar, the 15 SunBase^{TM} concentrating collectors are mounted in a N-S alignment behind the main barrel storage building. Figure 5.94 depicts a collector row, with the collectors in the non-collection position in night-time "stow" position with Fig. 5.95 giving a side profile of the collector.

The system installed at the Sonoma wine company consists of 15 of the SunBase^{TM} concentrating trough collectors, in 5 rows of 3 collectors. Each 12 m long collector consists of 24 (2 × 12) facetted glass laminate mirrors creating the parabolic trough reflector giving a concentration ratio of 8X on the triangular receiver. The combined PVT receiver has two receiving surfaces with the PV cells laminated into an elongated aluminium tile on each side. Each facet has three

Fig. 5.95 Side profile of the concentrating collector (reproduced with kind permission of Cogenra Solar)

Fig. 5.96 Detail of the combined PVT triangular receiver (reproduced with kind permission of Cogenra Solar)

absorbing channels combining at a small flow and manifold at each end of the collector. Figure 5.96 details the end design of the novel PVT triangular receiver.

The collectors are mounted on a central truss supported by two substantial structural columns at each end of the 12 m span. Each collector independently rotates along its central axis using a small electric motor, controlled using a predefined path based on the local solar characteristics, stepping at 1 min intervals. The structure is designed to withstand a wind loading based on winds at 87 mph.

Each collector is rated at 3.3 kWe and approximately 15 kWth, giving a combined PVT array output of around 272 kWe + th. The collected thermal energy and power is routed through the ground to the adjacent receiving plant station (Fig. 5.97). The power is connected to 5 SMA Sunny Boy inverters in the Sunny Tower configuration (ST48 8,000U 48 kW) (with an additional inverter built into provide redundancy back-up) mounted on the receiving station pad (Fig. 5.98). Each inverter receives the generated DC power from a row of three collectors. The collected thermal energy is transported by the 10% propylene glycol/water mixture (protection to −5°C) heat transfer fluid at a maximum design temperature of 50°C, with an upper limit of 70°C. The water is supplied to storage in two 2,500 US gallons (9,460 litre) externally insulated, storage vessels. Metres monitor the

Fig. 5.97 The solar electric and thermal routing into the ground from the collector to the receiving station

Fig. 5.98 The solar electric and thermal receiving station

supply of hot water and power to the winery. Power is directly supplied into the building grid and hot water is supplied to an intermediate storage tank after which the water can be further heated to 70°C for the facility production needs.

To maintain a suitable PV operating temperature, without ensuring a significant drop in performance, hot water is produced at a temperature not greater than 50°C. If the winery hot water storage (which is slightly over-sized to reduce the possibility of such an event) becomes saturated (i.e. is at 50°C) then solar collected heat is dumped to ambient via a fan cooled heat exchanger, to ensure optimal PV power production. The air cooled heat exchanger (Fig. 5.99) has four fans connected in

Fig. 5.99 The air cooled heat dump

series with a 'ramping' operation in place to deal with an increasing heat dump demand.

To date, the Sonoma wine company has been very happy with the solar facility. The system is estimated to provide the winery with 64,000 kWh/year electrical and 366,340 kWh/year thermal, realising substantial financial savings for the company. In addition, the company has enjoyed considerable media interest in this unique system and different form of energy provision. A measure of its unique status is borne out by the fact that the system was officially 'opened' in November 2010 by the former Prime Minister of the UK, Mr Tony Blair, who is also an advisor to the venture firm backing the company (Khosla Ventures).

5.3.2.11 Case Study EOS Estate Winery, Paso Robles, California

EOS estate winery is located in the heart of Paso Robles wine country. Originally named for the Goddess of the Dawn in ancient Greek mythology, EOS estate winery is a modern state-of-the-art facility, producing 220,000 cases/year. The EOS winery was originally built and owned by the Arciero family, who are still one of the largest wine-grape growers in the appellation. The winery opened in 1985 and was modelled after the monastery of Monte Cassino in Italy, near the Arciero family's hometown. In November 2009, the winery was acquired by the Saint James company. Since their introduction, EOS wines have consistently been recognised for outstanding quality (Fig. 5.100).

The spectacular 9,600 m^2 winery is set in their 700 acres of vineyards in the beautiful rolling Paso Robles countryside and boasts one of the most complete

Fig. 5.100 EOS estate winery

solar installations of any winery in all of California. Designed and installed by Conergy, the project began in 2008. The solar installation encompasses both solar PV and solar thermal and is both building and ground mounted and operates in tracking and fixed mode. The entire system can produce enough output to power and heat the water for the entire winery and tasting room operations. The details of the systems are presented below.

Photovoltaic Installation

Covering almost two acres, the 504 kWp single axis tracker photovoltaic system supplying the winery production facility is impressive. In addition, an extra 36 kWp of ground mounted fixed-tilt solar system powers the winery's tasting room. The 2,880 Conergy AG S 175 MU photovoltaic modules of the tracking system, rated at 175 Wp DC (1.33 m^2), are connected to 2 × 250 kW Xantrex inverters. The smaller fixed system has 204 Conergy AG S 175MU photovoltaic modules, connected to 6 × 6 kW Sunny Boy inverters (Figs. 5.101, 5.102).

Fixed-tilt PV System

- Function: supplies the electricity needs of the EOS visitor centre
- System size: 35.7 kWp
- Number of PV modules: 204
- Number of inverters: 6 × 6 kW
- Annual electricity production: 60,948 kWh

Fig. 5.101 Fixed tilt PV system supplying the EOS visitor centre

Fig. 5.102 Single axis tracker PV system supplying the electricity needs of the EOS winery production facility

Single axis tracker PV system

- Function: supplies the electricity needs of the EOS winery production facility
- System size: 504 kWp
- Number of PV modules: 2,880
- Number of inverters: 2 × 250 kW
- Annual electricity production: 1,002,000 kWh

During the winter months, for example December, the fixed system collects nearly 5% of its total annual yield due to its 25° incline due south. The tracking system, due to its flatter profile collects only 4% of its total annual yield during December. Conversely, during June the percentages of annual yield change to 12.5 and 10.5% in favour of the tracking system. Overall, on average, the tracking system collects up to 16.5% more energy per effective collecting area over the fixed system. In this installation, given the size of the tracking field, this is more than enough to warrant the additional cost in installing a tracking system over the fixed system. Typically, a single axis ground installation will cost an additional 18% upfront cost, which was covered in the US $3.8 million project cost (Fig. 5.103).

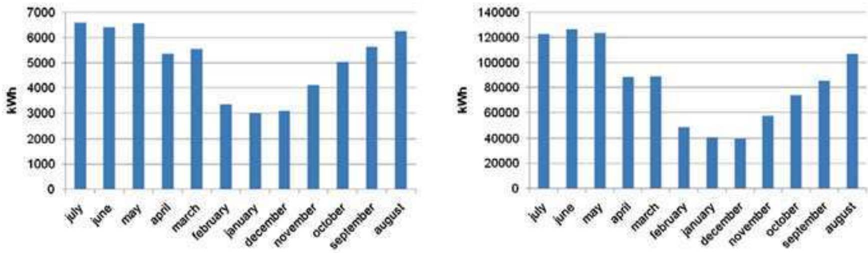


Fig. 5.103 Overall monthly kWh collection for the fixed system (*left*) and tracking system (*right*) for the EOS estate winery

Fig. 5.104 Roof mounted solar thermal collector array

Solar Thermal Water Heating System

In addition to the PV installation, 100 south facing Conergy F6000 flat plate collectors are mounted on the winery roof, to supply hot water to the winery. The collectors are connected in an indirect glycol mixture loop to the 11,355 l hot water storage tank via a plate heat exchanger, producing 4,500,000 l of hot water annually (Fig. 5.104).

The solar water heating system at the EOS winery production facility is impressive and represents one of the largest solar thermal installations in any winery in the US (Fig. 5.105).

5.3.2.12 Case Study Shale Canyon Wines, Boulder Creek, California, USA

Formed in 2007 Shale Canyon wines, is by Californian standards, a small producer. However, their size is more than compensated for by their dedication to producing wines of superb character from their 100% grid free winery. The combined winery/family residence, covering an area of 460 m^2, is designed and built to minimise energy use. From highly insulated structures to energy efficient

Fig. 5.105 Plate heat exchanger and hot water storage vessel

Fig. 5.106 The Shale Canyon Winery (reproduced by kind permission from Shale Canyon Wines)

systems and equipment, combined with good awareness and energy conscious operation, the electrical demand of the winery is such that it can be met through a stand-alone battery augmented 8.4 kWp DC PV installation with a 17 kW LPG backup generator (Fig. 5.106).

The PV installation system consists of 48 ground mounted Mitsubishi PVMF175UD4 (175 W) modules connected to a Flexware 1,000 Power unit (rated at 12.0 kW), complete with 4 Outback VFX3648 inverters (3.6 kW and 48 V), 1 Outback X-240 4 kVA Transformer, 3 Outback FM80 charge controllers and 1

Fig. 5.107 Image of the ground mounted PV installation (reproduced by kind permission from Shale Canyon Wines)

HUP Solar One 1,690 AH 33/48 V battery pack. The Flexware 1,000 Power unit is a pre-wired, 4 inverter, off-grid system for indoor installation with 48 V battery storage with a 120/240 V AC output (Figs. 5.107, 5.108).

Being one of only a few solar wineries that are totally independent of grid supply electricity, Shale Canyon wines have made a big statement to environmentally conscious winemaking. Figure 5.109 symbolically represents one of the main reasons why Shale Canyon wines opted for a solar installation and demonstrates their commitment to a sustainable product, both at a local level and beyond.

5.3.2.13 Case Study RayLen Vineyards and Winery, North Carolina, USA

Located in Mocksville, North Carolina, RayLen Vineyards and Winery is the only solar winery in the State. The winery, set in 115 acres of rolling vineyard at the southern end of the Yadkin Valley Appellation, is immediately obvious to the visitor with its distinctive cupola roof top. Operating as a dairy farm for nearly a century, it was not until 1999 when Joe and Joyce Neely purchased the property that a vineyard was created through the planting of the first vines. Today, there are over 35,000 European varietal grape vines, offering the guests a spectacular winding drive up to the winery. In its first three vintages, RayLen Vineyards and Winery has won over 200 medals at various state-wide, regional, and international competitions. Figures 5.110 and 5.111 presents the winery and PV installation.

The PV installation comprises of two fixed ground mounted arrays at a tilt angle of 22° facing due solar south (3° of magnetic south). Each array has 52 NexPower thin film 95 W modules rated at 4.94 kWp DC each, giving a total installation output of 9.88 kWp DC from the 104 modules. Each array is connected to a SMA

Fig. 5.108 Inverter and battery installation (reproduced by kind permission from Shale Canyon Wines)

Fig. 5.109 A good neighbour, Shale Canyon's visiting Bald Eagle (reproduced by kind permission from Shale Canyon Wines)

Sunny Boy 5,000 W inverter, located under the array (Fig. 5.112), mounted to the supporting frame structure. The PV arrays were mounted using a simple aluminium frame. No foundation base was necessary as the vertical mounting poles were inserted by up to 2/3 of their length, ensuring a very sturdy and structurally sound infrastructure to mount the modules upon.

The second (northern) array was arranged back to eliminate array shading by the southern array at any time of the year, as indicated in Fig. 5.113. Through simulation, an ideal location for the arrays was determined so that shading from the winery building and vines did not present a significant problem. Consideration was given to future proofing the installation with additional site space and electrical connections provided to allow an extra two arrays ($\sim$10 kWp DC) to be installed when circumstances are right.

Fig. 5.110 Front view RayLen winery with ground mounted PV installation to the *right*

Fig. 5.111 View from behind the winery with PV array in foreground

Fig. 5.112 View of the SMA Sunny Boy 5,000 W inverter

Fig. 5.113 PV arrays and subsequent shadows

The installation was designed and installed by Southern Electric Management. Initially, a bigger system was envisaged but, given administrative issues, the current PV installation was deemed more appropriate. The entire PV installation cost US $70,000, but with Federal and state subsidies, the total was only US $28,000. Coupled with favourable tariffs from Duke Power and a substantial solar renewable energy credit payment via Sol Systems, RayLen significantly reduced their electricity outgoings. In the 10 months since the installation, the PV installation has yielded 15,384 kWh resulting in an approximate 35–40% reduction in the winery's utility consumption.

5.3.2.14 Elderton Wines, Barossa valley, Australia

Elderton Wines is a small, family owned winery situated in the heart of Australia's Barossa Valley. First planted in 1894 by the Scholz family and then tended by Samuel Elderton Tolley, the Elderton vineyard was purchased by the Ashmead family in 1977. Taking only the best grapes from long established vineyards, coupled with a passionate dedication for quality, the Ashmead family have long been recognised as producers of some of Australia's best wines (Fig. 5.114).

In 2003, Elderton Wines moved into a new state-of-the-art winemaking facility in Nuriootpa. The new winery was a statement of the family's commitment to producing environmentally conscious wine, cementing their position as one of the leaders in sustainable winemaking within the Australian wine industry. To this end, the winery incorporates many features and systems that are designed to minimise energy consumption without compromising quality. Central to this philosophy is the PV installation located on the new winery roof which was the largest solar project undertaken by a winery in Australia at that time.

The Nuriootpa winery PV installation actually comprises 2 separate installations; a small 1.75 kWp installation mounted on the tasting room roof (completed in December 2007) and the larger 30 kWp system located on the winery roof (completed in September 2010). Figure 5.115 depicts the small 10 (175 W) module installation, tilt mounted in two arrays.

Fig. 5.114 The new Elderton Wines state-of-the-art winemaking facility in Nuriootpa (reproduced by kind permission from Elderton Wines)

The second, more substantial installation, comprises 180 Solaris modules, flush mounted modules onto the metal winery roof (Fig. 5.116) and covering an area of 216 m^2. The solar generator is connected to 5 wall mounted SMA Sunny Boy inverters as shown in Fig. 5.117.

The 30 kWp PV installation was designed to offset the winery waste water system and was sized to produce 75% of the daily demand or an average 150 kWh/day giving an estimated generation capacity of approximately 55,000 kWh/year. The complete installation cost Aus $175,000 and with a 'Retooling for Climate Change' Grant provided by Aus Industry, the winery only paid Aus $88,000. Elderton Wines are also fortunate to be connected to a generous Feed in Tariff at 42 c/kWh (State Government legislated) and 8 c/kWh from the local electricity supply authority. This tariff has since been capped for systems less than 10 kWp. Since the installation by Australsun, the system has operated flawlessly, exceeding the winery's expectations.

Fig. 5.115 The small 1.75 kWp PV installation mounted on the tasting room roof (reproduced by kind permission from Elderton Wines)

Fig. 5.116 The 30 kWp PV installation mounted on the winery roof (reproduced by kind permission from Elderton Wines)

5.4 Common Themes, Characteristics and Features

The previous sections catalogue the range and breadth of wineries worldwide that utilise active solar systems. It is clear to see that there are a great variety of solar installations in operation. Where financial assistance exists, PV is preferred.

Fig. 5.117 Image of the SMA Sunny Boy inverters for the 30 kWp installation

This is particularly prevalent in the USA and countries in Europe. Elsewhere, the case for PV is not so strong and solar thermal installations are greater in proportion.

As previously stated, the database, whilst comprehensive in parts, is not fully complete. Due to issues highlighted, information from some regions does not present a quantifiable total of the solar wineries that exist in that area. This is one of the main reasons that this chapter does not quantify the total installed solar collected capacity in a worldwide context. This collection of information on solar wineries does however, for the first time, represent an accumulation of knowledge which details the range and breadth of the solar winery concept permitting a review of the common themes, characteristics and features that are prevalent in solar wineries. Chapter 6 details this information relating to solar winery design in greater detail.

The vast majority of solar wineries utilise PV and almost all the PV systems installed are in some way grid-connected. Only one winery was identified as stand-alone operation, where PV generated power supplied battery storage, with a diesel generator backup. There is a clear distinction in the size of European installations compared to California. The average size of a Californian winery installation is 163.4 kWp whilst the average size for a European installation is 77.8 kWp, almost half. Only 2% of the identified PV winery installations in the old world were ground mounted, whilst almost a quarter of the installations in the new world regions were ground mounted, reflecting land availability issues.

A greater spread of installation type and mounting format was experienced in California. Fixed mounted systems represented the greatest share of PV installations, only 2–3% of all installations in the new and old worlds used a tracking mode of operation, mostly single axis, with a handful of double axis systems. In California, a further 3% of wineries opted for a combination of fixed and tracking operation. The data presented in Sect. 5.3.2.11 for EOS estate winery details the difference in performance for each form of operation. All the identified solar thermal systems installed were exclusively roof mounted and flat plate collectors were the most common. The range of manufacturers of PV modules and BOS equipment was greater in Europe, with no significant leader being recognised. In the USA, the range of manufacturers was smaller, with some common leaders identified.

A small number of wineries utilised both solar thermal and PV and whilst the majority of these had a small solar thermal system, a number of wineries did invest in substantial systems, capable of supplying a significant proportion of the winery's annual hot water demand. A few solar wineries took this a stage further and installed a solar thermal refrigeration system, thereby offsetting a significant electrical cooling load.

Although this database does not list other renewable systems used by wineries, it was observed that a small number of other wineries did use other forms of renewable energy. Solar energy collection, both thermal and electric, was by far the most common form of renewable technology used by any winery, given its particular synergies with the winemaking industry, but bio-fuels and wind were used by some wineries. Bio-mass, most commonly in the form of vine prunings, was used in a number of wineries. Anaerobic Digestion, micro-hydro, gasification and algae production was also observed. Whilst most wineries also operated good energy management and energy efficient practices, some wineries, due to the installation of a renewable (solar) system, gave less attention to energy usage due to being 'energy neutral'.

Economic considerations were the prime reason why a winery opted for a solar installation but equally important to a lot of wineries was environmental awareness and its relationship with market profile. It was therefore important for most wineries to promote the installation, this seemed to be more prevalent in the USA. Security of supply was a reason for a small number of wineries.

The vast majority of wineries that have invested in solar have broadly been very happy with their installation. It would, however, be fair to say that not all wineries had a perfect experience. There were some examples where poor design, installation and components have caused problems. In most situations, following a period of replacement or system modification, the problem was rectified. One common issue that seemed to appear a number of times was the under-estimation of the system output. Feedback from wineries indicated that due to a range of variables, the predicted system performance did not always match the observed output. As performance prediction tools have improved, coupled with designer and installer experience, the accuracy of predicted and actual performance has also improved.

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Chapter 6
Solar Winery Design and Operation

6.1 Introduction

The reasons why a winery would want to invest in a solar installation vary but they are generally based on financial and sustainable factors (economic, environmental and social), promoting a particular image or in some cases, to ensure energy security (Fig. 6.1). In many cases, it is a combination of a number of these factors. Whatever the reason, once the decision has been made to install solar, a detailed plan of action is initiated to ensure that the winery has the system that best suits their particular requirements.

As with any large solar installation, the project begins with a consultation period from which the appropriate design can be developed (with the existing financial and practical limitations taken into account). Once a design has been agreed upon, the installation process can take place. After installation completion following the required testing, commissioning and certification, operation of the system will officially begin. During the operating life of the system, a suitable maintenance and cleaning schedule should be initiated to make sure that the system is operating to its design potential. During this phase good observation and monitoring will ensure that any problems or issues are dealt with rapidly and appropriately. At this stage it may also be useful to instigate a public dissemination programme detailing the system and its potential benefits.

6.2 The Solar Winery System Design Considerations

The design of a solar installation for a winery follows very much the same process to that required for any commercial/production facility. Most of the initial factors to be considered will be based around the practical issues and constraints that exist in each individual winery project. First and foremost, the starting point will be 'thermal or electric'. For the vast majority of wineries both would be the answer as

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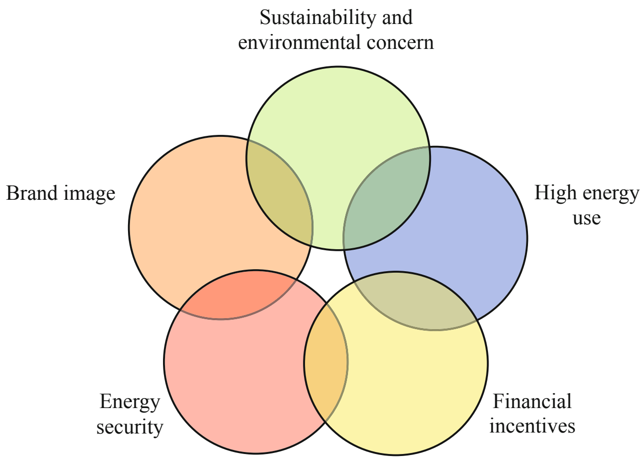


Fig. 6.1 Five reasons for the solar winery

all wineries have a large thermal and electrical demand. Unfortunately often cost or space availability will cause the winery to make a choice. Most have opted for PV, given the financial incentives that exist, although ease of operation and grid tie-in have been important as well. A larger proportion of smaller and mainly non-American wineries have opted for solar thermal. In California, some large solar thermal wineries do exist and their reasons for selecting solar thermal are interesting. One winery based in the Sonoma valley decided to utilise a solar thermal design based on the inefficiency of their electrical utilisation. Installing a substantial PV system would have just masked this inefficiency and would have 'solar offset' their need to do anything in improving the existing electrical equipment. Hot water production, however, with a modern gas boiler was efficient and utilising a solar thermal system to augment/replace this energy usage would yield a more positive environmental argument. Remaining funds could then be directed towards improving electrical efficiency before considering PV electric. For another Sonoma based winery, the decision came down to power security. The winery, being at the end of a long electrical supply network, wanted to ensure that during daytime production (at least) that they had a reliable power source. During a 1 year period, they had six power outages resulting from transmission problems. By utilising PV solar they could at least ensure that they had sufficient power to run crucial winery equipment. They even looked into battery storage but were put off by the costs. For the largest proportion of wineries that have adopted solar, most have opted for solar PV (for economic reasons), but a few wineries have opted for both PV and solar thermal with resultant energy savings.

The location of the main solar components (in particular, the collectors and modules) is always uppermost in any solar winery design. Every project is different but the majority are either building or ground mounted (that is the collection component). Utilising a suitable building structure (normally the roof) leads to

questions on the structural suitability, orientation, mounting angle, shading, physical access, component mounting, cable routing and so on. For ground mounted installations the availability of a suitable location becomes important. In the vineyard/winery context this is a very important consideration. Land for growing vines, particularly in quality wine producing regions, is very expensive. In one Napa valley based winery, 0.75 acres earmarked for a solar installation would lead to US $150,000 of bottled cabernet sauvignon being lost annually. Given this economic backdrop, designers are often forced into looking for alternative locations (close to the load). Steep hillsides, rocky ground, ponds or winery leech fields have all been utilised, each representing their own particular design challenges. In other situations, doubling up or combining a structural function has been utilised. Wineries are busy places with a wide range of activities and processes, including vehicle movement. Using awnings and overhangs or free standing structures have been popular as they can provide enclosures for equipment and resources or provide shade for car parking. Of course due care and attention must be given to vehicle size and turning circles. In addition, ground mounted systems tend to be located in the vineyard and thus represent a higher risk to vandalism or theft and the designer must be aware of the risk to reduce the problem.

Another design issue to be considered at the outset for a ground mounted system is fixed or tracking (although, not exclusive, most tracking systems are ground mounted). Tracking systems can yield typically 15% more energy over a year than a fixed system but the additional cost and lifetime operating requirements must be factored in at the beginning of the design stage and the winery informed of their implications.

Most wineries are situated in a rural location, beside the vineyards, although there have been an increasing number of wineries that are classed as being more urban in location, either through choice or circumstances. The increase in the public's interest in all things wine related has led to a greater emphasis on visitor access and a whole tourism industry has developed to satisfy this appetite. This has led some wineries to locate to urban or suburban locations or at least open tasting rooms in these areas, to make visits easier for the public. Conversely, this expansion has made once small agricultural centres expand to accommodate the wine tourism industry and thus encroach on what was once open vineyard land, bringing the wineries into an urban setting. The downside for solar in a urban setting means that there is a reduction in suitable (available) land for the solar installation, more potential shading conflicts and greater risk of solar vandalism or theft. This leads the designer to deal with a different set of issues and may impact the outcome for a given solar installation.

Another consequence of the expansion in wine tourism has been image awareness. Wineries are more aware of branding and the input of solar has not been overlooked. This of course can be a double edged sword, with a winery wanting to project an image of being green or sustainable, whilst another may be operating from an old historic building that needs to present a certain outward appearance that solar may conflict with. It really comes down to customer choice

and the balance of aesthetics versus solar access or visual prominence is not the preserve of the wine industry.

6.2.1 Solar PV System Design Process

The starting point for any PV solar installation begins with a site survey. A good site survey should be able to yield information relating to:

- The required size or output from the PV installation. Access to utility power bills and records, preferably 3 years or more, will give an indication of the typical load profile and annual power usage (kWh/year). This is very useful in determining the maximum system yield, particularly if there are other constraining factors. In addition, are there any planned extensions or refurbishments as they will effect power consumption.
- Details from the local utility company to obtain the required documents for interconnection and/or net metering (grid-connection) and review of the existing electrical system and the local interconnection requirements.
- Any special preferences that the winery may have with regard to system type, installation and location. Most winery managers (often the senior winemaker) are well informed and usually will have an idea of the system that they want. In areas that have a significantly high level of solar penetration (such as the Napa valley), the winery may want to adopt a system that their neighbour had installed.
- Architectural or aesthetic considerations. Quite often, the modern winery is built around a particular architectural rhythm or theme and therefore it may be necessary to make the PV installation prominent to the winery visitor or completely hidden from direct view.
- Operational constraints (vineyard/winery machinery). Wineries utilise a wide range of equipment and machinery therefore it may be necessary to consider seasonal use of equipment or turning circles for vineyard vehicles, for example.
- The financial background. The main reason for any site visit is to provide information for the system quote. Therefore, finding out what the winery is willing to spend and what grants or subsidies are applicable are of the utmost importance in defining the type and size of system installed.
- Suitable location for PV modules. In the winery environment there are many suitable locations for mounting the modules, typically the majority of systems tend to be roof or ground mounted, although the diversity of winery design has spawned a range of alternative locations, ranging from purpose made cover structures to the use of water treatment ponds. Of course key is the amount of area available and its distance from the load.
- Structural issues. Whether mounted on a roof or building element or free standing in an open space adjacent to the winery, the support of the modules requires careful consideration. It is therefore necessary to conduct a review of

the existing structure; roof shape, type, covering and sub-structure or ground topography, substrata and soil type. In addition, structural integrity must be considered; do we need to break through the roof or prepare a significant trench works.

- Orientation and inclination angles. Crucial to the overall system performance, the solar sun path most be determined for the given location. This is necessary to determine the optimal arrangement for the site; tracking or fixed, flush or tilted. Other concerns, however, many influence the decision on the optimal orientation or inclination angle, such as the building position, wind loading, visual intrusion, etc.
- Shading. Ideally the preferred location should be shadow free but it is inevitable that given the number of variables in site location, some shading may occur. Shading due to the location and shading resulting from the building (direct shading) are the prime concern. To evaluate the shading problem, a shading analysis should be conducted. This typically involves one or more of the following methods; site plan and sun path diagram, sun path diagram on acetate or shading analyser. For small systems one central point is used, on larger systems several points may be analysed.
- Equipment and cabling. Whilst the location of the modules is of prime importance, the location of the remaining balance of system (BOS) is also important. Typically the main components; the inverter, switch gear and meter are located close to the modules, but this is not always possible and therefore finding an available position may require some discussion and compromise. Issues of access, security, earthing and lightening protection, cabling routes and length, position of junction boxes and main AC connection need to be considered.
- Access and time constraints. Access for equipment or vehicles necessary to the installation process, given normal winery activities, must be considered. Furthermore, the modern winery operates over an entire year, with substantial increases in activity at least two or three times a year. It is important that these times are avoided, with the installation period planned to coincide with a quieter period in the winery's calendar. Local prevailing weather conditions must be considered (Fig. 6.2).

Information is key to designing a PV installation that meets the needs of the winery without compromising or hampering its day to day core activity.

In deciding upon a position to locate the PV modules, shading can offer a significant issue to the designer. In many cases it is clear that no shading conflicts exist but in some situations, the potential for shading requires that a shading analysis is conducted. In Fig. 6.3, due to the proximity of CO_2 extraction cowls on the roof of the winery, the module layout was designed to ensure that the shading was minimal; unfortunately even a small amount of shading can have a significant impact.

Sometimes the most unlikely objects can create a shadow and impact upon the PV performance. Figure 6.4 illustrates a shadow cast by a fence post put in place to protect the system from module theft. Figures 6.5 and 6.6 illustrate the conflict

Fig. 6.2 Module installation in an Italian winery with significant snow fall

Fig. 6.3 Module shading due to proximity of CO_2 extract cowls

that occurs between available roof area and the desire to maximise the PV collection surface. In these images shading by trees and other roof structures is obvious as is the shadow impact but in this particular example these problems were overlooked to ensure the maximum coverage potential, even with a reduced system efficiency.

Self shading can also represent an issue that needs to be considered. In a winery using two ground mounted arrays, software analysis was used to locate the arrays to ensure that shading from the adjacent winery was not possible and there was no self shading from southern array over the northern array at anytime of the year. A number of options were considered and a suitable mounting arrangement was selected with no shading, as indicated in Fig. 6.7.

In a study by Hain and Nee [6], the optimal PV system for a grid-connected installation in a wine producing co-operative situated in the south of France was determined. The wine producing co-operative facility consisted of four buildings;

Fig. 6.4 Shadow cast by post

Fig. 6.5 Soft shadow cast by tree

each with a double pitched roof in an east–west orientation. Although presenting a far from optimal mounting, due to a high solar resource the project was thought to be viable. In total there were eight mounting surfaces considered, giving a total mounting area of 1,398 m^2. Their study focused on evaluating the optimal configuration (layout, mounting structure, etc.) and generator and BOS sizing for the winery installation, given the specific site considerations. From an initial scoping study, the evaluation study centred on three suitable configurations; Option 1: Centrosolar Biosol SLP 190 Wp modules mounted on a SOLRIF structure, connected to Fronius inverters, Option 2: Centrosolar Biosol SLP 190 Wp modules mounted on a SOLRIF structure, connected to SMA inverters and Option 3: TENESOL Te 2200 230 Wp modules mounted on a SunOne structure and connected to SMA inverters. Given different roof orientations, at least one inverter was necessary per roof to ensure an effective MPP tracking.

Following detailed analysis of the physical restrictions and possible integration of the PV system to the available roof areas, including various module/structure

Fig. 6.6 Shadow cast by roof

Fig. 6.7 Array layout design to remove self shading

combinations, the design software packages PVsyst (University of Geneva) and PVsol (Valentin Energiesoftware GmbH) were used to simulate the installation and give an estimate of the potential electrical production. Both packages were used to consider near shading objects, module and inverter type, string configuration in addition to geographical position, local topography and available solar irradiation.

- Option 1 consisted of 864 modules, rated at 164.16 kWp DC, connected to six inverters with a total power of 150 kW, giving a specific yield of 1,063.96 kWh/kWp and an estimated output of 174,659.4 kWh/year.

Fig. 6.8 Significant snow fall on a thin film array

- Option 2 also consisted of 864 modules, rated at 164.16 kWp DC. However, due to the shading issues realised at the site, the generator was connected to 22 inverters with a total power of 164 kW, giving a specific yield of 1,119 kWh/kWp and an estimated output of 183,716 kWh/year.
- Option 3 consisted of 700 modules, rated at 161 kWp DC, connected to 22 inverters with a total power of 154 kW, giving a specific yield of 1,116 kWh/kWp and an estimated output of 179,627.24 kWh/year.

From the study Hain and Nee [6], option 3 was deemed to be the best. Using a larger number of (string) inverters the system was configured to the MPP which allowed for a better management of partial shadows. Option 3 with a specific yield of 1,116 kWh/kWp was only 0.3% less than option 2, but having a better economic return coupled with DC cable losses lower than 1% and a power mismatch between phases of lower than 2 kW, it was the most suitable configuration for this facility.

Snow can represent a problem for some solar wineries in certain regions during the winter months. Although the modules are robust enough to withstand the cold temperatures and increased weight, the snow does impact upon the system performance. With a slight slope, snow build up can be ‘persuaded’ to slide off but on more horizontally fixed systems shading can occur. In one Italian winery, utilising thin film modules rated at 382.8 kWp, the PV system generated less than 400 kWh

Table 6.1 Estimated PV area for 1 kWp output [4]

Cell material	Area (m^2) for 1 kWp
Polycrystalline	7.5–10
Mono-crystalline	7–9
Amorphous	14–20
High performance cells	6–7
CIS	9–11
CdTe	12–17

on a day with substantial snow coverage which was only 30% of the value generated the previous day when there was no snow (Fig. 6.8).

6.2.1.1 Solar PV System Sizing

The sizing of a given PV installation begins with module selection. As mentioned previously, this may already be decided upon, based on a customer's preference, installer's preference or supplier or simply cost and availability. Typically, however, the choice will be made on cell material (polycrystalline, mono-crystalline, amorphous, thin film CIS or CdTe) or module structure (framing arrangement, PV tile, glass module, etc.). Some designers make a preference based on localised sky conditions; certain thin film technology with a lower efficiency, can yield slightly more on diffuse conditions. Compared to crystalline PV systems, multi-junction thin film, amorphous silicon PV cells collect solar energy more efficiently during low light or diffuse conditions, particularly in the morning and late afternoon hours. In many climates, the majority of the solar irradiance is from diffuse lighting and since thin film PV technologies produce energy under lower irradiance levels over a given period of time, they can generate more power per installed Wp DC.

Once a module has been decided upon, a basic rule of thumb calculation is used to determine a rough estimate of the corresponding module area requirement. The following is a table listing some estimated areas needed for 1 kWp output Table 6.1.

At this stage, a rough approximation of the annual estimated output may be calculated. Based on an average a solar radiance chart (kWh/kW day) multiplied by 365 (days) multiplied by a system factor. The system factor takes into account module soiling, temperature, air movement, system configuration, shading, orientation, inclination angle, module efficiency, wiring and system losses and inverter efficiency. This can be useful in determining a rough idea of how much the system can contribute over a year to the winery's power requirement. This yield forecast can be as detailed or approximate as the situation dictates. Obviously, more specific detailing will give a more accurate forecast of the system's potential output. In some cases, physical on site monitoring may be considered, although this is time consuming and really unnecessary in most situations. In is now common practice to utilise simulation software to predict yield forecasts but the quality of the output is only as good as the information put into the programme. In some situations, other factors may constrain the size of the system.

The physical size or rating of the PV installation needs to be tailored to the system configuration (stand-alone or grid connected) and electricity load (and profile). The optimal size of a stand-alone PV installation is going to be completely different from that of a grid connected system. For a stand-alone design, the PV capacity based on the PV generating capacity and average load energy demand along with the system storage (battery) capacity (if present) must be known. Significantly over-sizing the system will reduce the cost effectiveness of the system, leading to a longer payback period.

Grid connected systems, in theory, can be as large as the funding or physical limitations will permit. However, in practice, this is not really an option for the solar winery. Apart from the physical constrictions, such as available space, some electricity utility suppliers will impose a limitation of the size of system and thus the solar generated electricity permitted to feed into the grid. This limitation is variable, depending upon location, but for the majority of solar wineries (certainly those based in California using net metering), the maximum size of solar installation has always been equal or less than the annual kWh requirement of the winery Portuguese legislation for example, limits micro production of green energy to the grid to 5.7 kW and no more than 50% of the building consumption power. If at the end of the metered year there is a surplus of electricity supplied into the grid, the additional amount is not recognised by the utility provider and thus is of no financial benefit to the winery. Typically, the designer will size the PV installation based on a fraction of the winery's average annual kWh load (usually 85–90%) and in this way the most cost effective solution can be designed for the winery, allowing for some flexibility in annual production variation or improved electrical efficiencies within the winery.

There are however, a number of wineries outside California that have taken advantage of lucrative feed in tariffs (FITs); generation or export based. Along with renewable energy certificates/credits (REC) or green certificates, solar credits and other similar schemes these incentives can have a significant impact upon the system selected and its final design. (Note: Just recently, the California Public Utilities Commission (CPUC) released a proposal that will require utility providers to procure electricity from renewable energy systems using FITs. This could have a dramatic impact upon the sizing and design of solar winery systems in California in the future).

Globally, tariffs and certificates differ depending upon numerous variables; power generation, installation place (building or ground), sizes and technology. For example, in Germany (with similar schemes in other European nations), FITs are highest for smaller installation (<30kWp), with incremental reductions for increasing PV system size and additional differences in rates relating to the mode of installation. These FITs are guaranteed for up to 20 years, an issue that has caused some resentment in Germany as power supply companies have increased their normal electricity tariffs to cover their increasing payments. Many non-PV augmented consumers believe that they are unfairly subsidising solar wineries and others to make financial gains at their expense. One obvious visual difference between a net metered installation and an installation using a FIT structure is the

Fig. 6.9 Single meter for a net metered installation (*left*) and double metering for a FIT metered installation (*right*)

number of meters. Net metering requires only one meter, whilst FIT systems require two; one to measure consumption, the other to measure PV generation. Figure 6.9 depicts differing meter installations. On the left, the single meter is a net metered solar winery in the USA and on the right, a FIT metered solar winery in Germany.

Using a power purchase agreement (PPA) or heat and power purchase agreement (HPPA) if using combined PVT (PhotoVoltaic-Thermal) is another option that is available to the winery. These agreements have become popular over the past few years and offer the winery an alternative method to utilise solar energy without the associated capital costs. A solar provider (perhaps in tandem with a financing company) installs the solar system at no cost to the winery. The winery is subsequently charged for the energy produced (at a lower level than their current utility rates). The direct benefits to the winery are a solar profile, lower energy costs, no up-front capital expenditure and perhaps a larger solar installation than it may have been able to afford using its own funds. On the negative, purchase agreements usually require the solar system to be large, ruling out smaller producers, and they have a complex, long-term contract that must be reviewed in detail. Contractual issues generally revolve around the cost of the purchased energy and terms of the agreement, end of agreement costs and renewable energy certificates/credits (RECs). RECs, as a trading commodity, are valuable to both the solar provider and winery and who owns the RECs, is often a problem. The winery wants the REC (and solar installation) to meet GHG targets and reduction plans, whilst the provider can sell them on to other energy users that cannot meet their targets.

Banks, of course, have not been slow in realising the potentially lucrative investments (loans, lease agreements, etc.) that exist and many have been very active in promoting their financial packages, particularly targeting wineries with younger owners and management. The designer should be aware of the local structures and financial support to ensure the most cost effective design for each individual winery. Many solar vendors also provide financing packages (Fig. 6.10).

The next design stage requires the designer to consider the conceptual design/layout of the installation and its relationship to the inverter(s). Although module

Fig. 6.10 Advertisement in bank window offering good financial packages for PV investment

inverter concepts are available, all the current solar winery installations utilise centralised or decentralised sub-array and string concepts, with varying ranges of voltage depending on the system size and module location and format.

In smaller centralised inverter installations, particularly those prone to shading, 3–5 modules may be connected in series in a string. In these shorter strings, the impact of shading on any module in the string has less impact on the overall array output. Of course, with numerous modules, this may lead to high currents and thus is less beneficial because of the resultant cable size. Longer strings (more modules) and associated higher voltages could be considered, with a reduction in cable size, but the impact of shading becomes greater and increased electrical protection is necessary.

Fig. 6.11 Arrays on different surfaces

As nearly all solar wineries utilise PV systems greater than 3 kW, they are all configured using the sub-array concept. In these installations, 2, 3 or more strings are connected to the inverter, resulting in a sub-array. This format allows many sub-arrays to be mounted at different angles or orientations (Fig. 6.11), given the availability of mounting space in the winery, allowing for better power related adaption to the localised insolation levels. It is important that all modules in the sub-array are uniform in mounting configuration and shading risk. Hain and Nee [6] present a study on the design and optimisation of a grid-connected PV installation in a wine producing co-operative with a number of buildings with various slopes and orientations.

One other aspect that the designer needs to consider in array orientation at this stage is tariff structure. Whilst the maximum PV collection will always occur at solar noon, equator facing for any given (clear solar) day, this may not in fact yield the best economic return for the winery. In situations where the winery (grid-tied) is on a net metering system or suitable agreed feed-in tariff, the optimal economic design may require the solar array to be mounted off its maximum solar collection orientation. Figure 6.12 demonstrates the difference in the maximum solar capture in kWh versus the tariff structure for a solar winery on 21st June 2010 and the subsequent saving resultant from the PV installation. In this particular system, the PV modules/arrays were flat mounted. If some of the arrays were realigned in an inclined south west (sloped) orientation, the resultant drop in the overall solar collection would be more than compensated by higher economic return due to the increase in collection in the late afternoon and thus electricity offset costs at the higher tariff rate.

Therefore, circumstances permitting, it may be more advantageous for wineries to utilise multiple surfaces with differing orientations to maximise the economic return on their investment.

Grants and other financial incentives, of which there are many variations of the basic grant to be found globally, can significantly reduce the cost of a solar installation to a winery (and hence reduce the overall payback period). However, in some situations, the installation of a PV system coupled with the installation of a new facility or refurbishment of an existing roof structure can produce even greater added value, reducing costs down even further. Whether new build or retro-fit, PV ready roofs can yield other added benefits to the winery, such as improved thermal performance (reduced cooling or heating loads), enhanced weather protection for the building, better sound proofing, and so on.

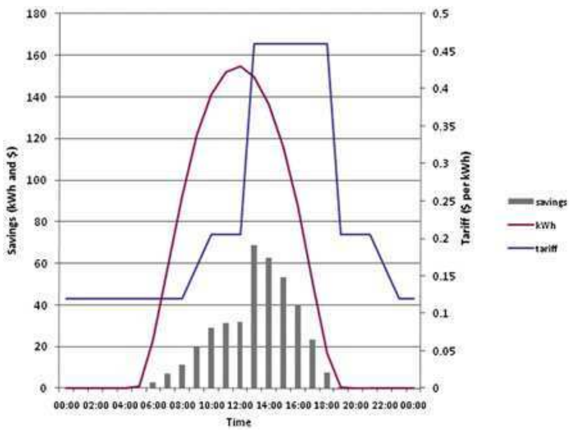


Fig. 6.12 Maximum solar capture (kWh) and tariff structure for 21st June 2010 with savings for a Californian solar winery [7]

6.2.1.2 The Sizing of the Inverter

The number and power rating of inverters are determined by the PV system output and system concept. Significantly under-sizing the inverter in relation to the PV system (up to 40% in some cases) was common previously. It is now, however, more normal to size the inverter on a 1:1 ratio between the PV array power and inverter power rating. Although the nominal power of the inverters can be ± 20% of the array output power, in many situations, the connected PV generator should be designed to be around 5% greater than the inverter's nominal AC output [4] which should be stated in the manufacturer's conformity declaration. Consideration must also be given to the inverter location (inside or outside), redundancy, voltage (based on modules per string) and number of strings. Section 6.3.4 also details considerations of the inverter with regards to mounting surface and shading considerations.

6.2.1.3 Cable Sizing

Cable sizing for PV installations should be conducted in accordance with national codes and regulations. In order to do this efficiently and effectively, the designer must determine the length of each cable (conductors) which will be dependent upon the module/string arrangements and relative positioning of the main components. Quite often, some form of schematic wiring diagram will help visualise the design. To size the cables correctly, the designer must know the cable voltage ratings and current carrying capacity whilst trying to keep cable losses and voltage drop to a minimum. In many situations, the DC cable must be kept to a minimum, having transmission losses less than 3%. In a PV system, cabling is defined as being module or string cabling, the main DC cable or the AC connection cable.

In many situations the weather, temperature and insulation will play an important consideration in cable selection but in a number of unique winery

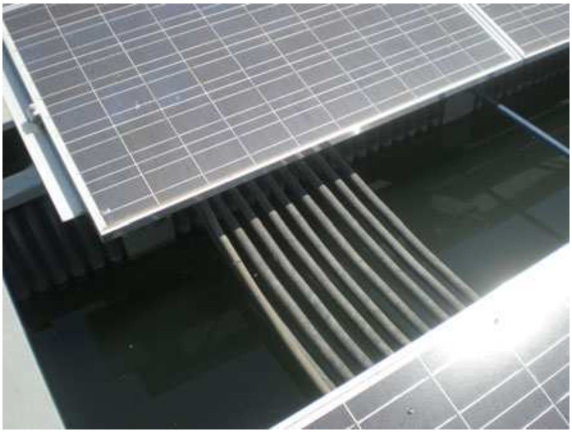


Fig. 6.13 ‘Floatavoltaic’ cable considerations

Fig. 6.14 AC and DC switchgear adjacent to the inverter

installations, water plays an even bigger design role. Figure 6.13 shows the heavy marine duty cabling that was specified for a ‘floatovoltaic’ installation.

6.2.1.4 Switchgear

In the event of a fault or to enable the inverter to be isolated from the PV modules/array a DC load switch is located close to the inverter. This main DC switchgear should have a load switching capacity rated for the maximum open circuit voltage of the solar array and short circuit current. In many cases, due to the outside location of the inverter, two AC isolators are specified; one near the load connection and one adjacent to the inverter. The AC switch should be double pole, labelled and lockable (Figs. 6.14, 6.15).

Fig. 6.15 AC switchgear and combiner and combiner boxes

Fig. 6.16 Unprotected module cabling (out of reach) on the underside of a PV carport structure

6.2.1.5 Cable Protection and Junction Boxes

The routing and connection of cables must not be underestimated. Wineries can be harsh environments, typically having high solar radiation levels, numerous washing activities and significant vehicular movement. All cabling should be enclosed with

Fig. 6.17 Combiner box with cabling from modules

Fig. 6.18 600 Volt junction box with conduit protection

Fig. 6.19 Combiner and connection boxes with flexible conduit protection

Fig. 6.20 String junction box with 12 string connections

Fig. 6.21 DC and AC cable installation from PV modules to the inverters and AC cabling from the inverters, respectively

mechanically robust conduit (or placed out of significant harm (Fig. 6.16) and PV array combiner/junction boxes should have protection to at least IP54 and be UV resistant (Figs. 6.17, 6.18, 6.19). In Fig. 6.20, however, each module cable is laid, exposed, within a cable rack to the string combiner box. In this example the PV modules are installed on an inaccessible roof and it was likely during the design phase that mechanical damage was not seen as a significant risk in this location. Likewise, Fig. 6.21 shows the process of cable installation on another inaccessible roof. In this example, perforated cable tray was selected to manage the cable networks. Figure 6.22 demonstrates the level of conduit protection that typically is afforded to DC cabling on an exposed flat roof or vertical column.

Figure 6.23 shows the internal path of a conduit for DC cabling inside a winery just below the roof on route to an internally mounted inverter station. The PV array covers the entire roof but due to architectural reasons, rather than make the roof

Fig. 6.22 Conduit protection for DC cabling on a flat roof (*left*) and cantilever carport installation (*right*)

Fig. 6.23 Conduit protection (*top right*) inside the winery on route to the inverter

termination at the end closer to the inverters, the conduit was introduced at the far end of the roof. Whilst this was aesthetically superior, this path required a substantial amount of additional cabling, conduit, fixings and labour, not to mention an increase in voltage drop.

For ground mounted systems the potential for mechanical damage increases, therefore in many installations the cabling is trenched both from the arrays (DC) to the inverter stand and back to the load (AC). Figure 6.24 depicts cable routing protection during the installation phase.

6.2.1.6 Earthing (Stand-Alone)

A good earth arrangement should provide a well defined, low resistance path from the stand-alone PV system to earth. This earth conductor must be as large as the largest conductor in the system. Two types of earth are necessary in PV systems; the system earth and equipment earth. For the system earth, one of the current carrying conductors, usually the negative, is grounded at a single point. This establishes the maximum voltage with respect to ground and also serves to discharge surge currents induced by lightning. Any exposed metal equipment (such as equipment casings and frames) that can be physically touched should also be earthed. This will limit the risk of electrical shock should a ground fault occur. The

Fig. 6.24 Buried conduit routing giving protection for DC cabling to the inverters and AC cabling from the inverters

Fig. 6.25 Copper earthing electrode rod

earth rod requires good contact with the ground that it is embedded into ensure a low resistance (Fig. 6.25).

Fig. 6.26 Snow covered lightning protection conductors

6.2.1.7 Lightning Protection

PVs do not increase the risk of the building getting struck by lightning but because of the large surface area or the high elevation relative to the surrounding terrain required by the photovoltaic arrays (and wiring systems), PV systems may be at particular risk during lightning discharges during thunderstorms, which are more prevalent in the hotter wine producing regions of the world. Little can be done to protect the PV equipment from a direct lightning strike. Surges caused by near strikes occur more frequently and the severity of possible damage depends on the distance from the strike to the array. Lightning surges can damage PV modules and inverters and therefore need some form of protection. If the winery has an external lightning protection system, then the modules should be located within the protective area of an isolated air-termination system. The PV system should not, however, interfere with the existing lightning protection measures. This means keeping a sufficient separation distance between the PV framing and the external lightning protection system to prevent uncontrolled spark-over. In many situations, the PV arrays cover the whole roof structure. In these situations the frame must be integrated into the external lightning protection. Commercially available surge protection devices (movistors and silicon oxide varistors) are available. They are normally installed in the array DC output/input to the inverter and on the AC output from the inverter. Installing the PV conductors in grounded, covered metallic conduit will decrease susceptibility to lightning (Fig. 6.26).

6.2.1.8 Solar PV System Design Software

Whilst simple hand calculations or rule of thumb processes are sufficient in determining a rough approximation of the system characteristics, nearly all PV

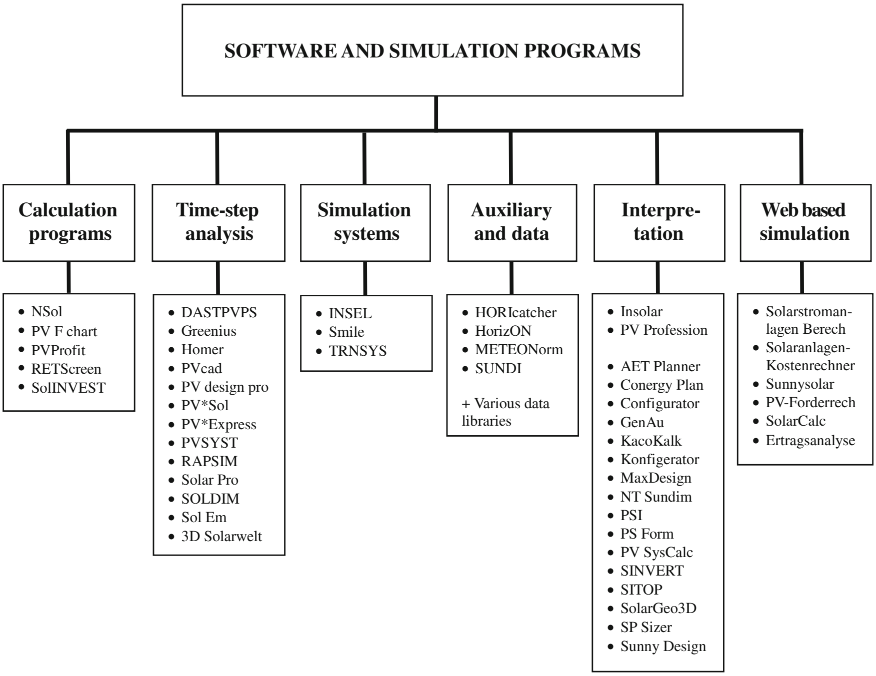


Fig. 6.27 Classification of sizing and design software [4]

designers will use some form of software to plan, design and optimize the system in detail. That is not to say that some basic calculations should be omitted. They can be very useful in arriving at a 'ball-park value' which can be compared against the final software design system. Sizing and simulation software enable the designer to produce the most suitable system for the winery by analysing a wide range of different system configurations. The wiring variations possible, for various module and inverter configurations are significant but by using software the designer can evaluate many wiring options to predict the system output at different locations, different tilt angles and under numerous weather conditions. Designers can also evaluate system economics, structures, shading, amongst many other outcomes. The range of software available to the designer is significant (Fig. 6.27) gives a range of the programs available.

6.2.2 Solar Thermal System Design Process

Similar to a PV solar design, the starting point for a solar thermal system design also begins with a site survey. A good site survey should be able to yield information relating to:

- The required size or output from the solar thermal installation. Access to (hot) water usage and combustion fuel bills and records (both DHW and process), will give an indication of the typical daily, monthly and seasonal load profiles. This is very useful in determining the maximum system yield, particularly in ensuring that the system is not oversized and stagnation is avoided. In addition, are there any planned extensions or refurbishments, as they will impact consumption.
- Any special preferences that the winery may have with regards to system type, installation and location. Most winery managers (often the senior winemaker) are well informed and usually will have an idea of the system that they want.
- Architectural or aesthetic considerations. Quite often, the modern winery is built around a particular architectural rhythm or theme and therefore it may be necessary to make the solar collectors prominent to the winery visitor or completely hide them from direct view.
- Operational constraints (vineyard/winery machinery). Wineries utilise a wide range of equipment and machinery, therefore it may be necessary to consider seasonal use of equipment or turning circles for vineyard vehicles, for example.
- The financial background. The main reason for any site visit is to provide information for the system quote. Therefore, finding out what the winery is willing to spend and what grants or subsidies are applicable are of the utmost importance in defining the type and size of system installed.
- Suitable location for collectors. In the winery environment, there are many suitable locations for mounting the collectors. Given transfer heat losses, the majority of systems tend to be roof mounted and close to the storage tank.
- Structural issues. Whether mounted on a roof or building element or free standing in an open space adjacent to the winery, the support of the collectors requires careful consideration. It is therefore necessary to conduct a review of the existing structure; roof shape, type, covering and sub-structure or ground topography, substrata and soil type.
- Orientation and inclination angles. Crucial to the overall system performance, the solar sun path most be determined for the given location. This is necessary to determine the optimal arrangement for the site. Other concerns, however, many influence the decision on the optimal orientation or inclination angle, such as the building position, wind loading, visual intrusion, etc.
- Shading. Ideally the preferred location should be shadow free but it is inevitable that given the number of variables in site location, some shading may occur. Shading due to the location and shading resulting from the building (direct shading) are the prime concern. To evaluate the shading problem, a shading analysis should be conducted.
- Equipment and piping. Whilst the location of the collectors is of prime importance, the location of the storage tank, piping and control devices is also important. Pipe routes and length, position of fittings and valves need to be considered.
- Access and time constraints. Access for equipment or vehicles necessary to the installation process, given normal winery activities, must be considered.

Furthermore, the modern winery operates over an entire year, with substantial increases in activity at least 2 or 3 times a year. It is important that these times are avoided, with the installation period planned to coincide with a quieter period in the winery's calendar.

Information is key to designing a solar thermal installation that meets the needs of the winery without compromising or hampering its day to day core activity. Using consumption data from existing literature is often misleading, particularly in the case of wineries and it is therefore very important that this information is directly gathered from the specific facility.

The consumption profile and the target hot water temperature must be ascertained. Over estimation of the hot water requirement will lead to over sizing of the system. Typically, a temperature of 60°C is necessary at the store for sterilisation purposes of DHW space heating water temperatures may be higher. However, 60°C is generally too high for hot water outlets and a temperature of 45°C is usually preferred. This can be attained by mixing the hot and cold supply before the outlet, or where local drinking water regulations permit, directly from the store. Generally, the heat yield of the solar collector (and system) significantly increases with a reduction in the required temperature in the collector circuit.

The solar yield, solar fraction or solar savings fraction is the amount of energy provided by the solar thermal system divided by the total thermal energy requirement of the facility. Determining the correct solar fraction is of great importance in arriving at the correct size of solar installation for a given winery. Whilst a solar fraction can be calculated for any time period, it is commonly related to an annual requirement and therefore must consider seasonal influences and requirements. The choice of system size often comes down to a question of high levels of primary energy substitution or providing solar heat at a very low cost.

If a high level of primary energy is to be substituted, the solar system coverage must be as high as possible. There is however, a practical upper limit. If the solar system is designed to provide a 100% solar fraction, and the system is sized on the lowest solar availability, it would be grossly oversized in the summer, leading to a significant overspend in the system, dumping of heat and the potential for system damage. In a temperate zone (which most winemaking regions fall under) the solar fraction for a solar water heating system is therefore most efficient at around 50% per year for a commercial application. At this fraction, the system will provide nearly all the summer heating requirement whilst providing a pre-heating role in the other months.

On the other hand, if system installed cost is the issue, the highest possible system utilization (kWh/installed m^2) is required and will tend to mean that the solar fraction will be much lower. With a smaller amount of collected thermal energy, the collector efficiency will be higher (Fig. 3.69), resulting in higher kWh/unit area. In a temperate zone the preferred solar fraction for this scenario will between 10 and 40% per year, generally 25% for most typical calculations. Table 6.2 details a basic rule of thumb for solar thermal sizing in a temperate region, supplying hot water at 60°C, with continuous water draw-off, with an optimal collector orientation and tilt.

Table 6.2 Basic rule of thumb for solar thermal sizing in a temperate region

System component	Temperate climate (based on 1,000 kWh/m^2/year)	
	25% solar fraction	50% solar fraction
Collector surface area	0.5 m^2/50 l of hot water/day	1.25 m^2/50 l of hot water/day
Storage tank capacity	30–50 l of tank volume/m^2 of collector surface area	50–70 l of tank volume/m^2 of collector surface area

The design of the system for a winery is additionally complicated with the variable hot water demand profile over the year. Whilst a consistent hot water demand exists throughout the year, the maximum demand usually occurs at the harvest/crush period (normally in September or October in the northern hemisphere). These profiles can be further influenced by the winery process activities (for example, onsite bottling or hospitality).

In most large scale solar thermal installations today, due to the complexities in system design and operation, determining the system performance, economic and environmental considerations and overall work plan, a simulation program is utilised. A good simulation program should be able to provide the optimal components and system configuration for the winery. It must, however, be understood that any simulation package is only as good as the initial information input and that it is vital that the system designer has good technical grasp of the subject. There are a wide variety of solar thermal simulation programs available, catering for design and planning consultancies, installation companies and research and development. Most manufacturers will also produce packages that are tailor made for their products. Simulation programs can be classified according to their programming process. The following lists the process descriptions and common packages available:

- Calculation programs. These are simple programs that are based on static calculations, usually based on average monthly values. They can provide most of the necessary system parameters and are relatively quick. They do not deliver detailed system information and can be quite restricted in the configuration options they provide. The f-chart program is one of the best known and widespread used calculation programs.
- Time step analysis programs. These programs permit a more dynamic evaluation over a given time period. Using averaged weather data in sometimes hourly intervals, a greater level of detail can be provided. The programs tend to have user friendly interfaces, but sometimes require experienced users. Some of the common packages in this bracket are T*Sol, Polysun, GetSolar, RETScreen and FRESA.
- Simulation systems. In more complex systems, a dynamic simulation of the system is necessary. Simulation system programs offer more versatility but require greater time to input the information and need trained users to operate. The programs permit a greater level of integration at a multi-zonal and systems level. Some of the common packages in this bracket are TRNSYS and SMILE.
- Tools or auxiliary programs. These programs are generally small tools to help provide supplementary assistance and information in tandem with the other simulation programs. Some tools are SUNDI and METRONORM.

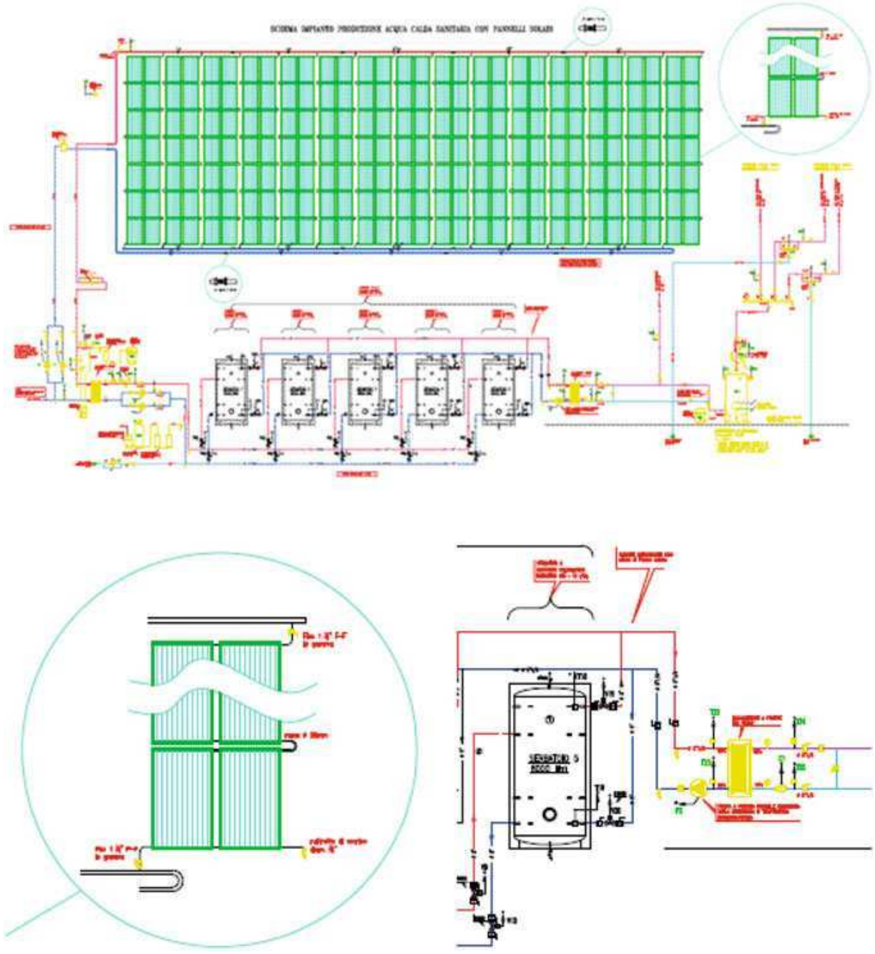


Fig. 6.28 Solar thermal system detail for a large Italian winery (reproduced by kind permission of the MezzaCorona Group).

Figure 6.28 details the schematic system design for a solar thermal system in a large Italian winery

6.3 Solar System Design Considerations for a Winery

The design issues relevant to any large production facility are relevant to a winery. Once a suitable collection (and/or storage) system has been sized and specified, the issues are primarily based on the practical considerations and constraints dictated by each individual winery set up. The most important consideration is the

Fig. 6.29 Ballast system with a shallow tilt on a flat roof

placement and mounting of equipment and distribution of service networks and these are dependent upon the type of installation; thermal or PV, fixed or tracking.

6.3.1 Fixed Structures

In solar wineries, a wide range of fixed mounting arrangements are utilised. The vast majority are either ground or building mounted but there are a number of different formats, perhaps unique to the wine industry.

6.3.1.1 Fixed Roof Installations

The majority of solar installations in wineries are mounted onto the building, primarily the roof. However, a number of different roof mounting systems are available based on the roof format; flat or sloped. Whether mounted on a sloped or flat roof, the mounting arrangements can be grouped according to the connection to the roof, rail or frame arrangement and module fixing mechanism.

Flat roofs offer the greatest flexibility to the designer/installer as the collectors can be oriented and tilted to the optimal collecting format. For flat roofs, the options are:

- Roof connection: ballast system, anchoring and direct fixing to the roof
- Frame: support/mounting rails, angle brackets, trays and base
- Module fixing: point clamping, clamping strip and flushed fitted

A number of solar winery mounting examples are shown in Figs. 6.29, 6.30, 6.31, 6.32 and 6.33

In some cases, the collectors can be integrated into the roof elements and used to provide thermal insulation, helping to reduce the winery's cooling load whilst protecting the roof from damaging UV rays and thermal degradation (Fig. 6.34).

Fig. 6.30 Fixed directly to a flat roof

Fig. 6.31 Sealed anchoring foundation on an almost flat roof

Fig. 6.32 PVs mounted on a flat roof using hollow concrete strip slabs

The system shown uses the Powerguard® photovoltaic roofing system, incorporating Sanyo HIP-195BA3 tiles. The PV tiles are backed with insulating polystyrene foam and connected together with interlocking tongue and groove side surfaces.

Fig. 6.33 Solar thermal flat plate collectors mounted on a flat roof using a RSJ beam support, directly fixed to the roof structure

Fig. 6.34 Detail of Powerguard® lightweight building integrated photovoltaic roofing system

Around the perimeter of each array, RT curbs are fitted to resist wind uplifts whilst providing ballast to ensure installation stability without the need for roof penetration.

Sometimes in a retrofit installation it is necessary to alter the building structure to accommodate the solar collectors (Fig. 6.35). In an Italian winery, a substantial number of PV modules were proposed. However, the existing flat roof space offered no available space to mount the modules. The solution was to remove the existing roof light features and utilise the upstand structures to mount the modules (Fig. 6.36). Figure 6.37 shows the final installation. A number of roof lights were maintained, to provide some daylight to the space below, as shown in Fig. 6.38 on a very wintery day.

It is important to select the correct mounting/fixing arrangement for flat roofs without compromising the integrity of the roof seal or restricting access to the roof. Using a tilted arrangement but mindful of the possibility of over shading, the created gap allows a certain amount of access between the collectors. However, adding some form of tilt can increase the wind loading and this, in combination with the fixing method, must be considered before the appropriate mounting mechanism is decided upon. Ballasted systems are beneficial in that it is not normally necessary to penetrate the roof but can only be used on roofs that can structurally support the extra weight. Anchored systems generally require some

Fig. 6.35 Roof tile integrated PV arrays in a winery in Sicily, Italy

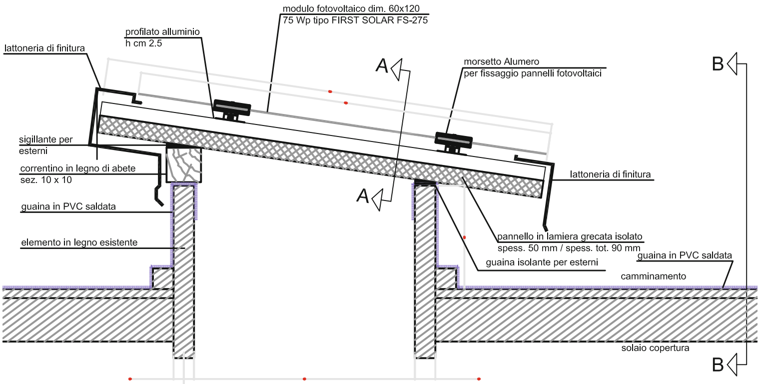


Fig. 6.36 Detail of the adapted roof light upstand structure (reproduced by kind permission of the MezzaCorona Group)

Fig. 6.37 Final installation of the adapted roof light upstand structure (reproduced by kind permission of the MezzaCorona Group)

Fig. 6.38 Remaining roof lights between PV arrays

Fig. 6.39 Flush mounted PV modules on several suitable south facing roofs with appropriate tilt angle for the location

form of roof penetration which should be kept to a minimum but, once fitted, offer a range of mounting frame options to be explored.

In sloped roof installations, the orientation and module tilt can already be predetermined. However, some flexibility exists. Figures 6.39, 6.40 and 6.41 depicts three of the common roof/solar collector mounting forms installed on winery buildings.

Figure 6.42 illustrates the problems that can arise when the PV installation, for aesthetic reasons, is designed around a particular roof form. In this instance a number of Sharp 185 Watt modules have been adapted to fit around a roof valley. The 4 years of installation have led to discoloration and encapsulation impairment. Triangular modules are available, although it is unknown whether this was an option at this installation.

In sloped roof arrangements, the collectors are fitted just above the existing roof finish (tile, shingle, metal, etc.). The aim is to provide some form of self supporting structure, generally requiring some form of roof penetration to anchor to a suitable roof sub-structure element. For sloped roofs, the options are:

- Roof connection: roof hooks, mounting tiles, seamed roof clips and hanger bolts
- Frame: single or double layer support/mounting rails
- Module fixing: point clamping, clamping strip and flushed fitted

Fig. 6.40 Flush mounted PV modules with moving tilt angle following the curvature of the roof

Fig. 6.41 Tilted (fin) PV modules to face south with appropriate tilt angle for the location

Fig. 6.42 Poor installation of PV modules

The choice of roof fixing mechanism depends upon the roof (Fig. 6.43). Whichever mount is selected it must be sufficiently sealed to prevent any water ingress. It is highly unlikely that individual collectors will be independently mounted on these fixtures and therefore it is normal to have a rail/frame structure set above the roof onto which the collectors are mounted. Depending on the collectors and array size, a single or double (cross beam) rail arrangement can be selected. A number of examples are shown in Fig. 6.44.

Fig. 6.43 Roof overhang providing shade and protection for the inverters

Fig. 6.44 Single layer support/mounting rails for a PV installation and solar thermal installation on sloped roofs

Fig. 6.45 Double layer support/mounting rails for a PV installation on a sloped roof

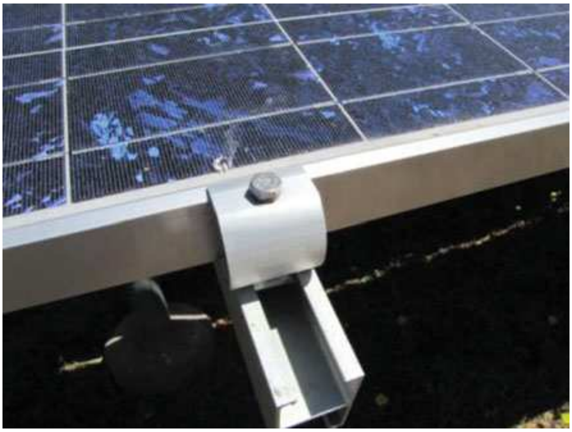


Fig. 6.46 Module point clamping

Fig. 6.47 Difficult bolt head access

Fig. 6.48 Linear strip with point clamping

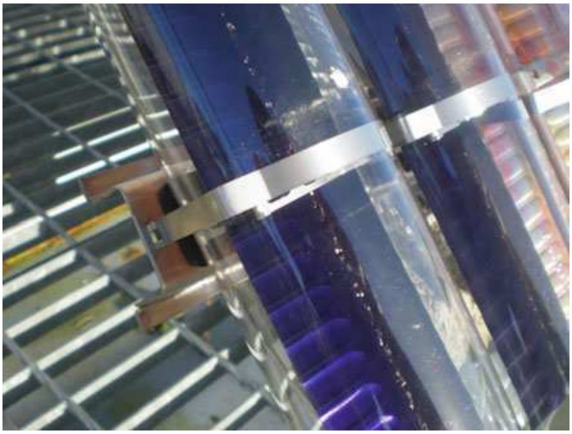


Fig. 6.49 Rail and metal strap fixing for an evacuated tube collector

Fig. 6.50 Lightweight pole mounted system located above a winery leech field

A common form of support/mounting rail arrangement used in many winery roof installations is Unirac's SunFrame system. It is a slim-line structure that is engineered to sit low to the roof without gaps. Unirac offer a range of other alternative mounting systems to suit specific situations.

Fig. 6.51 Metal poles driven directly into the unprepared soil

Fig. 6.52 Metal rails driven into the unprepared soil

For both sloped and flat roof installations, once a suitable sub-frame assembly has been provided, the modules or collectors need to be securely fixed into position. The common methods used are point clamping, clamping strip or flushed fitted. In many instances, the method of fixing is influenced by security. This is a particular issue for wineries and is dealt with in a later section (Figs. 6.45, 6.46, 6.47, 6.48, 6.49).

6.3.1.2 Fixed Ground Installations

For ground mounted systems, the framing and collector fixture mechanism are similar to that of roof mounted systems. The ground fixture mechanisms, however, differ significantly and are greatly influenced by the ground soil conditions and underlying geology coupled with the surrounding topography. As many wineries are in rural locations, remote from any local sewage network, the leech fields or

Fig. 6.53 Metal poles mounted in cast concrete piles; on sloped hillside (*left*) and flat ground (*right*)

soak-away spaces can offer a substantial area of land suitable for mounting a solar installation that would otherwise be unusable (Fig. 6.50).

From the solar wineries that have opted for a ground mounted system, the majority use either concrete strip, slab or pile foundations to secure or directly fix the frame structure to or they simply drive/screw steel posts into the ground. The option of using a complete pad foundation (covering the entire site) or stone gabions exists, but no solar wineries have utilised these forms of base structure to date. The following figures depict some of the commonly used methods.

Driving steel poles directly into unprepared ground is certainly an easy option, allowing simpler removal if necessary. However, as a rule of thumb, to be effective the poles must be pushed into the soil to a depth of approximately 2/3 of the length of pole. This can be difficult if the underlying soil is quite shallow and the substrata is hard or rock. In addition, consideration must be given to the effects of weathering, corrosion and movement. Where this form of ground fixing is difficult, some form of pre-cast or in situ concrete structure most be used. Whilst this form of foundation is more time consuming, costly and requires earthworks, the support produced is generally more structurally sound and is particularly necessary where the collectors are tilted with increased wind loading (Figs. 6.51, 6.52).

A pad or heavy cast concrete foundation would be impossible or very costly to utilise on uneven or sloped hillside, therefore the forms of foundation depicted in Figs. 6.53 and 6.54 are ideal. In many wineries, any available flat land is used for vineyards and therefore in many situations the only land available for the solar installation is rough or sloped marginal land.

Most wineries have tended to use the previously described methods of foundation or ground connection. However, in some situations, where larger structures and soil conditions dictate, more robust foundations have been utilised (Figs. 6.55, 6.56).

Due to the exposed nature of many ground mounted systems in wineries, the main frame structure is usually bigger and more robust than a building mounted system. Figure 6.57 depicts a vertical galvanised steel pole to which a galvanised

Fig. 6.54 Metal poles mounted in cast concrete piles on undulating topography

Fig. 6.55 Large concrete slabs with in situ cast mounting poles

Fig. 6.56 In situ concrete casting of bolting mechanism for a carport cantilever design

steel box section is welded. An aluminium rail frame is fixed via a bolted clamp to the box section onto which the modules are mounted. A roof mounted arrangement would typically only require the rail frame. Figures 6.58 and 6.59 show alternative

Fig. 6.57 Robust galvanised steel pole and box section main frame structure

Fig. 6.58 Robust galvanised steel tube section connected to rack via U bolt

Fig. 6.59 Adjustable rack fixing

Fig. 6.60 Main frame structure made from pre-formed galvanised sheet steel purlins

Fig. 6.61 Individual non-tracking pole mounted PV arrays

forms of ground system rail fixing. In an effort to reduce the structural components, and thus reduce the weight and cost, formed galvanised sheet steel purlins offer a lightweight alternative. Figure 6.60 shows an elevated ground structure using horizontal purlin cross beams on vertical purlin columns. The framework is strong enough to support the modules with design wind loading yet light enough to avoid over specification and thus cost of the structure (Fig. 6.61).

The vast majority of mounting and racking/rail systems utilise steel in some form or another. However, timber can also be used. Figure 6.62 illustrates the use of timber in a PV carport structure. In this example, timber was selected as the main structural element to maintain an architectural balance within the winery.

6.3.2 Tracking Sructures

In a few wineries, the additional energy capture provided by a tracking installation was preferred. Most of these wineries use single axis horizontal tracking systems

Fig. 6.62 Main frame structure made from timber

Fig. 6.63 Single axis north–south tracking system on a box axle

(no single axis vertical systems were recorded). Horizontal trackers pivot on a long horizontal tube/beam which is supported on bearings mounted upon a structural frame. The axis of the tube is on a north–south alignment. The collectors are mounted on a rail frame fixed to the tube/beam which rotates on its axis, tracking the apparent motion of the sun through the sky. As they do not tilt towards the equator they are not as effective during the winter or at higher latitudes. However, during the spring, summer and autumn seasons when the solar altitude is relatively high, they are at their greatest collection potential. This horizontal operation offers a simple, robust tracking operation and as the collectors are horizontal they can be compactly placed on the axle without the risk of self shading. As with ground mounted fixed system with significant tilt angles, it is necessary that a significant foundation is used to support the collectors, frame and tracking mechanisms. The foundation and frame should be designed to withstand the worst case wind expected in the area. Reinforced concrete with anchor bolts is recommended (Fig. 6.56).

The single axis horizontal systems in operation in wineries use various motor/mechanical mechanisms to control collector row movement. Figures 6.63 and 6.64 depict two differing styles of module rack fixing to the horizontal axle.

Fig. 6.64 Single axis north–south tracking system on a tubular pivot

In Fig. 6.63 the main axle is a box beam. In this particular design, the importance of the bearing is crucial to the operation. In Fig. 6.65 the consequence of utilising a polymer bearing is obvious. In this example, after only a few months in operation the plastic bearings have worn and broken under the constant tracking action. In some points, the bearing has fallen out leading to metal on metal contact. This action has increased friction and thus loads upon the tacking motor causing a lower operational life. To date the winery has had a number of tracking failures due to motor destruction. Tracking systems are expensive but it is important not to use inferior materials and components as these can compromise an entire installation.

Figure 6.64, with a tubular pivot, augmented with damping cylinders, offers a smooth movement. Of course, this system is much smaller than the former and therefore does not have the same load acting upon it. Both systems also utilise a slightly different motor/rack and pinion mechanical arrangements to transfer the motor movement to the modules. In each case, the parasitic power required for the motor is small, typically only requiring a single 1.5 HP motor. Figures 6.66 and 6.67 details the differing motor/gearing mechanisms associated within the systems mentioned previously. Figure 6.68 demonstrates a different collector and tracking option. Again, the system is a single axis north–south tracking mechanism, but this time the collector is a parabolic trough PVT unit, utilising a small, column mounted motor that turns the central axle in 1 min time-step adjustments, using pre-determined sun path information for the location.

Single axis vertical trackers are another option, where the collector plane pivots about a vertical axis with the collectors mounted either vertical or at a tilt. There are no vertical systems being used in any solar wineries to date, however, by providing a simple adjustable (periodic) tilt mechanism, these trackers are capable of seasonal tracking on two axis. Figures 6.69 and 6.70 depicts double axis trackers in wineries in the Sonoma Valley and Spain, respectively.

Fig. 6.65 Single axis bearing wear and tear

Fig. 6.66 Motor/gearing mechanism used in a large single axis north–south tracking systems

An image of a double axis tracking PV installation in a Sicilian vineyard is shown in Fig. 6.71. In this system, one axis is fully automated, whist the second axis requires a number of annual adjustments.

Of course, the motor(s) require power. This leaves the designer with a choice between active or passive tracking. In passive tracking systems, the motors that move the mounting frame use no photovoltaic power, thereby having less failure opportunities. Active systems, however, optimize PV power collection.

Fig. 6.67 Motor/gearing mechanism used in a single axis north–south tracking systems

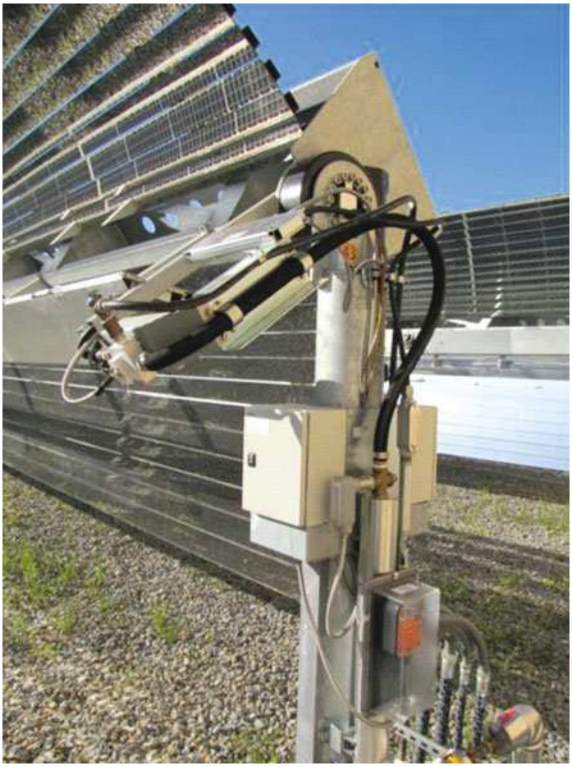


Fig. 6.68 Motor mechanism used in a parabolic trough PVT single axis north–south tracking system

6.3.3 Other Structures

Not all wineries have buildings (roofs) that are suitable for mounting a solar installation and in some situations there is no land available or the cost of

Fig. 6.69 Double axis tracking system beside a vineyard

Fig. 6.70 Double axis tracking system in a Spanish winery

Fig. 6.71 Double axis tracking system in Sicily, Italy

offsetting valuable vine growing space is too much. In these situations, wineries have come up with some novel arrangements to incorporate their solar system (Fig. 6.72).

Wineries tend to have a lot of outdoor activities or vehicles on site. It is due to these factors that a number of wineries have considered using a free standing,

Fig. 6.72 PV carport installation

Fig. 6.73 Significant structural elements used in a PV carport installation

purpose built structure to combine both a structural support for the solar installation and provide a shaded environment for car parking, winemaking processes or storage of materials and equipment.

Carports offer an excellent opportunity to offset the costs of a PV installation with a shading structure. There are many variations available, enclosed or open sided, utilising a flat, sloped or mansard roof style. However, due to the size and height of system required, considerable care must go into the each system and a detailed structural evaluation is necessary to ensure that the system will be structurally robust. Figure 6.73 indicates the level of structural support that may be necessary.

Of the few solar wineries that have opted for a carport structure, most have utilised an open, flat roof (or near flat) style. Figure 6.74 pictorially demonstrates the various stages in the fabrication and assembly of a PV cantilever installation at Schug winery, California. The cantilever design, with less vertical structural supports, offers greater flexibility and access to the space below the PV canopy. This offered Schug winery an ideal space to locate bulky storage containers.

Due to a lower number of columns, the columns that are used need to be significantly larger to accommodate the loading effects of the canopy framework, PV modules and wind effect. This subsequently requires the foundations to be larger. Figure 6.74a shows the cast concrete (and shuttering) with reinforcement

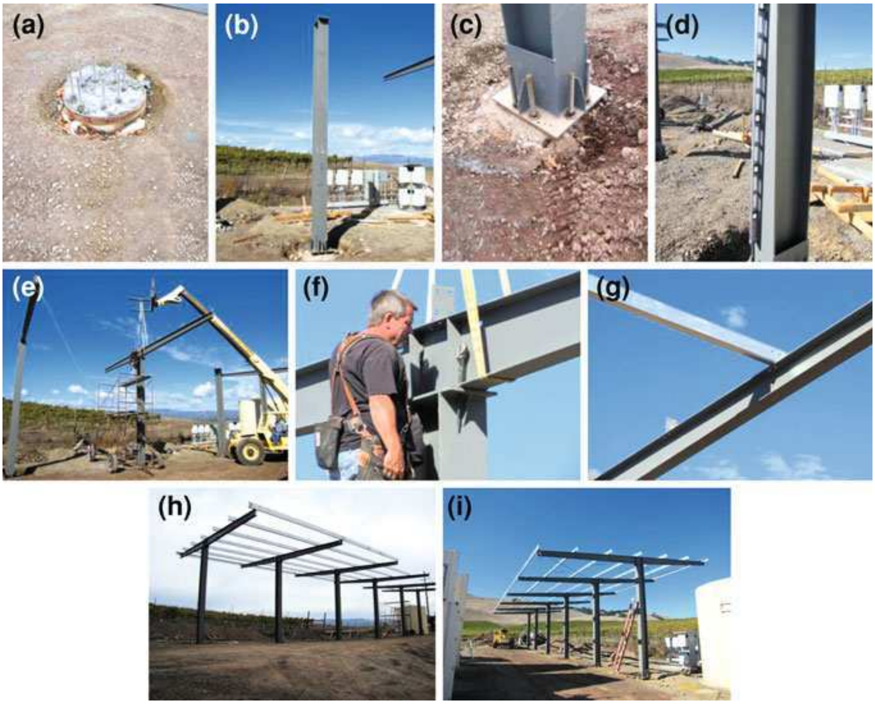


Fig. 6.74 Step by step preparation and assembly of a PV cantilever installation

and embedded bolting rods. Figure 6.74b–d shows the erection of one of the main supporting columns. Once in place the base of the column is tightened down and the checked for alignment. Any deviation at this stage would have significant implications during the later stages of assembly. Next the main structural (cantilever) beams are hoisted into place and secured (Fig. 6.74e, f). To give the structure rigidity, the cross purlins (onto which the PV modules will be directly mounted) are fixed into position (Fig. 6.74g, h) and cross ties fitted across the diagonal spans (Fig. 6.74i). The structure is completed and ready to accept the module installation (Fig. 6.75).

As previously mentioned, available mounting space in a winery is sometimes difficult to find. In many wineries, a significant area of the property is given over to treatment or water storage ponds. This ‘dead’ space has been viewed as ideal for the mounting of PV systems both around the pond area or in some cases over the pond. Figure 6.76 shows the PV installation at the Trefethen Family Vineyard in California where the array is mounted into the pond berm, facing almost south.

In a couple of wineries, the need to find an alternative site has lead to the use of ‘Floatavoltaics’. Whilst this offers a mounting space with no economic downside and yields a complimentary benefit in providing shade for the pond, thereby reducing surface evaporation, and getting an evaporative cooling effect on the

Fig. 6.75 The completed PV cantilever installation

Fig. 6.76 The pond berm PV installation at the Trefethen Family Vineyard, California

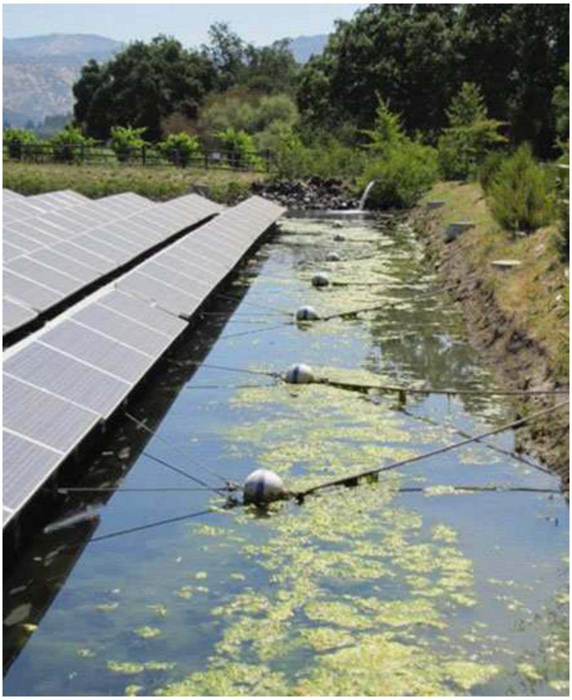
modules, there are a number of structural problems associated with this design concept.

The surface of the pond is never constant and over a period of a season, the pond can vary by up to 3 m. A simple solution would be to mount a fixed frame over the pond but the associated cost and disruption, not to mention the issues of working over the pond, makes this a prohibitive option for the winery. Thus utilising a floating system became the obvious choice. The modules are fixed to a series of pontoons. Each pontoon is made from two concentric plastic, ribbed drain pipes, sealed with the inner pipe filled with expanded polyurethane foam (Fig. 6.77), supporting approximately 8 PV modules each.

The pontoons are designed to rise and fall with the level of the pond. However, allowing the PV arrays to move up and down will also allow the PVs to move from side to side, moving from their optimal collection position and perhaps sustaining damage. The action of the wind is the biggest contributor to unwanted movement, particularly as the modules are tilted and present a larger capture area. Therefore, to reduce/remove this lateral movement, the PVs and pontoons must be securely fixed to the pond banking. Figure 6.78 details the mooring of the pontoons via

Fig. 6.77 Pontoon systems on two differing 'floatvoltaic' installations

Fig. 6.78 Rigid steel cabling fixed firmly to embedded concrete columns on the pond banking



rigid cabling fixed firmly to embedded concrete columns, whilst Fig. 6.79 illustrates a semi-fixed/cable arrangement on another 'floatvoltaic' installation.

Figure 6.79 shows the use of a fixed bracing (with pivot) to allow the PV system to move with the changing pond level. In this design, the fixed bracing provides a greater deal of rigidity over the cable only design and to allow for the difference in pontoon location, relative to the banking, the mooring cables at the back of the system have heavy duty springs integrated into the cabling. In both

Fig. 6.79 Semi-fixed/cable arrangement with a pivoting steel arm at the front of the array and a cable arrangement connected to embedded concrete columns on the pond banking at the back

cases, the significant concrete mooring structures can be seen, with the cast piles being typically sunk up to 1.5 m into the ground.

In addition to ensuring that the system is securely fastened, the system must provide an access gangway to permit periodic routine maintenance and cleaning. Figure 6.80 shows the gangway with pivoted attachments to accommodate the changing level of the irrigation pond.

All PV installations will have to cope with the extremes of the local environment, sunlight (UV), precipitation, temperature fluctuations and air movement. However, a ‘Floatovoltaic’ installation and the proximity to water requires an increased level of protection. Generally all connections and enclosures should be rated to at least IP56 and, where a potential risk of submersion exists, the protection should be higher. To provide a safe connection to the land based inverter(s), suitable marine grade insulated cable is utilised as shown in Fig. 6.81. The effects of localised increased corrosion must also be considered.

A ‘Floatovoltaic’ installation can have other indirect benefits. The shading effect from the PV modules and mounting system reduces the amount of solar energy incident on and thus absorbed by the pond, lowering the thermal gain by the pond, reducing the average water temperature and thereby reducing the rate of surface evaporation from the pond. This is an important consideration in an environment where water conservation it very important. The PV modules being located so close to a large body of water can take advantage of the localised cooling afforded by thermal transfer and evaporation. In one winery, the modules on the ‘Floatovoltaic’ installation had panel temperatures that were up to 2.8°C less than the land based modules located adjacent to the pond.

Algae growth in ponds can be a problem. It was observed in one pond that there was fewer algae per unit of surface area than would be otherwise expected. Having a large portion of the pond covered with a PV system would tend to suggest that

Fig. 6.80 'Floatovoltaic' gangway access

Fig. 6.81 Cables coming ashore in a 'floatovoltaic' installation

some impact on the local micro-environment would result. No measurements were conducted to confirm or deny this claim. One disadvantage of this format of PV installation is distance. Of the two winery 'Floatovoltaic' installations in operation, one is so far from the load that it is used only for vineyard pumping loads and the other required a substantial power transmission infrastructure to be installed to supply the power generated to the winery.

6.3.4 Main BOS Equipment

Once a suitable size and type PV generator system has been decided upon, including mounting structures, all of the remaining components are sized and specified accordingly. This leaves the designer with the task of finding a suitable location and mounting arrangement for the remaining balance of system, namely the inverter(s) or inverter configuration(s), switchgear, cabling, junction boxes and

Fig. 6.82 Internal wall mounted Fronius inverters (*left*) and floor mounted Xantrex inverters (*right*)

monitoring systems. The optimal arrangement is to have the inverter(s) and main switchgear located as close to the PV arrays and AC load connections as possible, reducing the amount of cabling needed, keeping losses and costs to a minimum. This is not always possible, particularly in retro-fit installations and often a series of design compromises are necessary.

The winery, as stated previously, can be a harsh environment for any equipment. The positioning of PV installation equipment is no different. Generally, an indoor location is preferable for the inverter and associated switches as this provides a cool, dry, dust free environment. Figure 6.82 shows inverters mounted indoors in winery buildings. Using an indoor location, however, requires ventilation and heat dissipation and as such multiple inverters should be spaced to allow good air movement around the units, not blocking any grilles or heat sink surfaces. This may mean installing a dedicated ventilation supply and/or extract (Fig. 6.83). In some instances, humidity may also be a factor to consider. Inverters can be noisy, so the impact on the surrounding space must be considered. These example wineries, are the exception, in nearly all other solar wineries, the inverter(s) and main switchgear are located outside.

Where an inverter(s) and switch gear installation is located outside, the unit enclosures should have protection to not less than IP54. This should provide adequate protection to enable them to withstand external weather conditions. The position should provide good access to enable monitoring, regular maintenance or system replacement to be carried out without undue complication. Being in a prominent position may require additional protection, from unwanted attention and vandalism to damage arising from vehicle activity. Figure 6.84 depicts the use of bollards around the inverter to prevent accidental vehicle damage. Whilst the inverter should be designed and manufactured to withstand direct solar exposure for prolonged periods, where possible, it is advisable to shade the equipment. Exposure to the elements can over time lead to a reduction in service life and thus a little additional design attention and/or cost can make a significant difference in system operating life. Thus shading is always preferable, and where the installation permits, shading afforded by building elements (Fig. 6.84), the PV arrays

Fig. 6.83 Internal floor mounted Siemens inverter with dedicated inverter room and accompanying ventilation system

(Fig. 6.85) or mounting/building structures (Figs. 6.86, 6.87) should be utilised. Where existing structures are not available, purpose built structures have been erected to provide cover (Fig. 6.88).

Appropriate shading for inverters was highlighted in one Californian winery's experience (in the Sierra foothills) with external inverters. The 14.4 kWp installation had external inverters that, due to direct exposure to the sun, kept overheating and switching off to avoid burning out. Over a period of 6 years, this on/off cycling reduced the output from the installation by nearly 35% of the initial estimated output. Only by moving the inverters inside did the winery start to realise a significant return on their investment.

In a winery, particularly where visitors are being entertained at the facility, the inverter and associated equipment, because of noise, appearance and unwanted attention are usually located in a position far from public view. Very view wineries have deliberately installed their systems in a prominent location. However, some have and because of this, the quality of the installation is of a higher specification. Figure 6.89 shows an inverter tower in full view to the public visiting the winery.

In many large installations (>50 kW), with a common plane of collection, due to cost issues, it is far more convenient to utilise one large inverter. However, opting for a modular inverter design (using string inverters of <10 kW) has several

Fig. 6.84 Inverter located on the north side of the winery with good shading and bollards providing a level of protection from accidental vehicle damage

Fig. 6.85 Inverter located on the underside of the PV array

Fig. 6.86 Inverter located under a PV carport (with bollard protection)

Fig. 6.87 Inverter located under an overhang from the winery (with bollard protection)

Fig. 6.88 Inverters located in a purpose made cover structure

benefits; allowing for multi-planar installations, greater 'total' reliability and security of supply, easier to incorporate into the winery building, thus improving visual impact and lowering noise output. Figure 6.90 shows a fraction of the 45 inverters installed indoors on an installation greater than 300 kWp. A typical string inverter weighs about 30 kg which makes any refurbishment tasks easier to complete, particularly in inaccessible locations. Micro-inverters (<1 kW and normally equivalent to module ratings) are especially applicable for sites with shading issues since each individual solar module can be optimized for maximum solar production.

Hain and Nee [6], from a study of a winery installation mounted on various roof structures of different orientations and slopes, suggested that an installation utilising 22 inverters over six inverters provided a better specific yield (1,063.96 kWh/kWp compared to 1,119 kWh/kWp). Furthermore, the power mismatch between phases was lower than 2 kW. In this project, the power was supplied in three phases, yet the SMA inverters were single phase. In many European installations using single

Fig. 6.89 PV inverters and mounting tower in full view of visitors to the winery

Fig. 6.90 Modular inverters approach

phase inverter devices, supplying in three phases, the inverters must be balanced across the phases with power 'top-up' compulsory for phase imbalances greater than 5 kW. This has a particular impact upon the design and connection of PV modules/strings/arrays with their respective inverters, not only in terms of nominal power but throughout the day with differing solar inputs.

In large PV installations, the inverter(s) and switch gear can be a substantial size and weight. It is therefore necessary to provide sufficient foundation for mounting. In some wineries, an existing suitable mounting platform exists [paved

Fig. 6.91 Fully exposed inverter mounted on an existing pre-cast concrete surface

Fig. 6.92 Lightweight pad foundation to support inverter rack and tower mounting structures

area or structural element (Fig. 6.91)], but in many a dedicated structure is necessary (Figs. 6.92 and 6.93). Due to the nature of the inverter and associated load, pad foundations are the most common form utilised.

The presence of rainwater run-off is not to be ignored. Figure 6.94 clearly demonstrates the impact that unchecked rain water can have in the erosion of stable ground around a PV installation. In this instance, the winery has had to put in temporary containment measures to reduce the removal of soil from under the PV foundations. Unchecked, this problem could cause subsidence and impact the ability of the system to effectively collect solar energy. Minimising water run-off through low impact development (LID) and integrating ecological and environmental considerations, such as good landscaping or selection of porous paving materials into the PV site can significantly reduce this problem.

Site cabling (from the PV generator to the inverter(s) and from the inverter(s) to the load/grid) can be a significant issue for some wineries. The associated issues are varied but most relate to physical and operational constraints, grid/metering problems and associated distribution losses and economic reduction.

Fig. 6.93 Substantial pad foundation with wall to divert ground rainwater run-off

Fig. 6.94 Problems with rain water run-off

Far Niente in California installed the first large scale ‘Floatavoltaic’ installation onto the winery’s one-acre grey water retention pond. The initial concept was to connect the solar array into an adjacent meter that serviced the small electrical aeration pumps on the pond. The local electricity authority stated that this was not possible and suggested that they run the cabling from the arrays directly through a meter in the winery, well over 1 km away. Digging a trench this long would not only be costly, but it would also cause disruption in the vineyard and to other buried utilities. A compromise was found, whereby the cables could be run through an abandoned 150 mmØ underground irrigation main that ran from the pond to the winery. Considerable refurbishment was necessary with access points created every 80 m or so. The access points in the now completed trench can be seen in the middle ground in Fig. 6.95.

Further issues arose when it was realised that the existing supply authority connection would not be sufficient to carry the power generated by the solar installation. As a reduction in the PV system size was not a feasible option, a new 500 kW transformer (Fig. 6.96) located on a neighbour’s property was the only viable option. Luckily, a utility easement existed and their neighbour was willing to help out, provided Far Niente paid for putting the utilities underground.

Given the distances encountered, particularly with ground mounted (or pond) systems, often hundreds of metres from the meter/grid connection and/or winery,

Fig. 6.95 Trench and cabling from inverters to winery meter

Fig. 6.96 The 500 kW transformer located on the neighbour's property

a number of wineries have developed their own 'mini solar grid' to accommodate the dispersed utility supply issues. Long Meadow Ranch Winery in California developed a 'mini solar grid' within their property to combine three existing utility services into one and incorporated efficient transformers to minimize line loss.

Another example demonstrating the additional equipment and thus cost associated in connecting a PV installation to the grid is illustrated in a German solar winery. As per current German legislation, systems in excess of 30 kWp DC (per installation, up to a maximum of two installations) are not illegible for an authority funded grid installation. The winery must therefore incorporate these additional interconnection costs within their overall budget. In this particular winery installation, rated at 287 kWp, an additional €109,000 was needed to cover the cost of the new interconnection overhead transmission line and transformer. Figure 6.97 details the transformer/meter unit with the overhead transmission line in the background. In many cases, this cost may increase the payback period, rendering the project unviable economically.

Fig. 6.97 A three phase 415 V–20 kV transformer and overhead grid connection

Fig. 6.98 Underground AC cable in a dedicated service trench

Figure 6.98 shows another example of cable management. In this installation, the AC cable is run from the transformer across a paved vehicle access space to the transformer (and grid connection) in a dedicated service trench.

The vast majority of wineries opt for some form of grid connection and, from the review of wineries worldwide with a substantial solar installation, only one winery (Shale Canyon Winery), due to its distance from the grid, has opted for a completely stand-alone mode of operation. The entire electrical demand of the

Fig. 6.99 Internal solar thermal plant (control unit, plate heat exchanger, expansion vessels and pumped glycol collector and hot water storage loops)

winery is met through a stand-alone battery augmented 8.4 kWp DC PV installation, with a 17 kW LPG backup generator. The PV installation system consists of 48 ground mounted Mitsubishi (175 W) modules connected to a FLEXware 1,000 Power unit (rated at 12.0 kW), complete with four outback VFX3648 inverters (3.6 kW and 48 Volt), one OutBack X-240 4kVA transformer, three outback FM80 charge controllers and 1 HUP solar one 1690 AH 33/48 Volt battery pack.

6.3.5 Thermal Storage Tanks and Equipment

In addition to collector requirements, the need for additional space to accommodate the remaining equipment in a solar thermal installation is no less important than that required in a PV installation. In reality, the requirements are more important in that substantial heat loss occurs in the transmission of the collected energy. Therefore, the thermal store must be located as close to the collectors as possible with consideration given to the hot water load (and heat exchangers). Section 3.5.2.2 detailed the various solar thermal collector/store configurations. The most common installation format utilised within solar wineries consists of an external glycol mixture collector loop connected via a plate heat exchanger to a main solar thermal storage vessel. Figure 6.99 shows the complete thermal transfer components, excluding storage vessel and collectors. The figure details the collector loop and hot water tank loop connected via a small plate heat exchanger (centre). The glycol and hot water expansion vessels can be observed either side of the heat exchange (grey-glycol mixture and red-water). Both loops are pump circulated. This compact system was capable of delivering 4,500,000 l of hot water annually.

Fig. 6.100 External glycol drain back tank

Figure 6.100 illustrates a slightly different approach installed in a winery in Sonoma, California. In this example, a (external) propylene glycol mixture drain back tank to collect glycol from the collectors and pipes, to prevent overheating or freezing. When the external temperature drops near to 0°C or the storage tank reaches 93°C, the system shuts down automatically and the glycol flows into the drain-back tank.

As the majority of solar thermal winery installations tend to be retro-fit, the preferred mode of installation utilises a dedicated solar tank which is directly connected to a main thermal storage vessel heated by the auxiliary heating system. In the larger installations, the dedicated solar vessels are located externally and heavily insulated. Accommodating these tanks within these wineries is not usually a problem. The tanks are simply located adjacent to the external fermentors, utilising the same mounting structures, or located in the winery's general external plant area. Figure 6.101 illustrates a typical external thermal tank (11,355 l), located outside beside the presses and fermentors.

Alternatively, a number of wineries have opted to locate the solar hot water storage vessels indoors. This is convenient where no space restriction exists or heat loss from the vessels does lead to an increased cooling. Figure 6.102 depicts combined bio-mass and solar hot water storage vessels with pressurisation vessels located in a dedicated plant room.

Fig. 6.101 External thermal storage vessel tank (11,355 l)

Figure 6.103 shows an example of a solar PVT installation installed in a winery through a HPPA (Heat Power Purchase Agreement). In this situation, the winery does not own the facility and so to facilitate the operation and maintenance of the equipment, the solar provider (Cogenra Solar) needs full access to the site. Therefore, all the main components are mounted upon a dedicated plant pad with good site access and sufficient service space around the equipment. Metered heat (and power) enters the building directly from the external storage tanks into the main hot water storage tank with auxiliary back-up heating. Figure 6.104 details some of the main components.

Of the solar thermal wineries identified, the vast majority utilise the solar generated hot water for domestic and process (washing) applications. Given the constant hot water demand throughout the year, it is surprising that more wineries have not opted for this type of solar installation. Cost (lower economic incentives) seemed to be the biggest barrier.

Most wineries have a continuous cooling demand and two wineries were identified that utilised solar generated heat to provide cooling (in addition to hot water applications). Figure 6.105 depicts the novel NH_3/H_2O absorption refrigeration plant, developed by Pink GmbH, installed in an Austrian winery. The plant

Fig. 6.102 Internal hot water storage vessels

Fig. 6.103 External dedicated solar plant pad

is supplied by heat from the flat plate collector array, augmented by bio-mass back-up, to produce chilled water to be used in direct air cooling for the wine bottle store. This was the company's first operating prototype and required the room shown in Fig. 6.105 to house the main equipment (excluding the cooling

Fig. 6.104 External expansion vessel and plate heat exchanger

Fig. 6.105 Internal solar thermal absorption refrigeration plant

Fig. 6.106 Differing physical barriers employed by solar wineries (*left*) standard industrial fencing and (*right*) decorative fencing

tower which was located directly above on the roof). Their latest prototypes are more compact, requiring significantly less space.

6.3.6 Other Winery Specific Issues and Concerns

In discussions with wineries that have a solar installation, two common issues always seem to be prevalent, namely security and cleaning, although many others exist as well. Both security and module cleaning are not exclusive to winery systems but the nature of the winemaking environment make these particular issues more important.

6.3.6.1 Solar System Security

Most wineries are located in rural locations giving thieves near perfect conditions to avoid detection. Solar installations, in particular PV installations, represent very lucrative targets for criminals primarily due to their cost, exposed nature and ease of removal. Over recent years there has been an upsurge in the number of PV module thefts. In the Napa Valley in 2009 hundreds of PV modules were stolen from wineries. In June alone over 300 modules were stolen, prompting local wineries to look at making their investments secure and installing anti-theft measures [5]. PV damage resulting from vandalism can also be an issue for many urban locations. Fortunately for solar wineries vandalism has not been a reported problem.

The mechanisms available to the winery range from simple low cost measures to complex, high cost technologically advanced systems. Many of the methodologies used are commonly used in other security applications but some have specifically evolved to meet the requirements of the solar winery market. Each method has their benefits and must be considered on a case by case basis.

Remember, most wineries are open to the public and visitors are welcomed. Creating 'Fort Knox' does not present the image that many wineries want. The following are some of the common methods currently being used.

Site Location and Landscape

Choosing a suitable location for the solar collectors is primarily always due to solar access, with security being of lesser importance. They are however, not mutually exclusive. Generally placing the collectors on a roof or building structure, or mounting on an elevated structure, simply places the collectors out of reach. In addition, being usually located close to the building load, the presence of staff can also be a deterrent. Where placing the collectors in an inaccessible position is impossible and using a ground mounted system at a remote location is the only option, good landscaping can be utilised to conceal their presence to casual visitors or provide a physical barrier to access.

Physical Barriers

Whilst landscaping can be used to provide a barrier to unwanted access, it is easily penetrated and does not provide a significantly robust deterrent. Therefore, more structurally sound, usually metal based, barriers in the form of railings, fences, palisades and gates are preferred. There are many differing styles of physical barrier that can be employed ranging in cost, appearance and protection afforded. The final choice will depend upon the location and preference of the individual winery. Figure 6.106 illustrates the difference in appearance of some fencing arrangements employed by two solar wineries; functionality verses aesthetics. In complimentary symmetry, solar power is utilised by many wineries to provide power to the security system, an example of this is shown in Fig. 6.107 where two wineries employed powered gates, one directly from power from the solar winery and the other via a dedicated stand-alone system.

Physical Connection

Solar collectors normally require some form of fixing device to ensure that they remain in place under operational conditions, for example wind loading. This typically consists of some form of bolting mechanism, strapping or guide arrangement. All too often, however, these are easy to break and recently the use of security fasteners to attach modules to the supporting structure or steel cable/chain to secure the modules to each other have been used to add another layer of complexity in collector removal. Figure 6.108 shows three different fixing bolts with increasing levels of difficulty to overcome. At one Napa Valley solar winery, which used security bolts on their PV modules, the

Fig. 6.107 PV power gates; (*left*) a main gate power via the solar winery and (*right*) a stand-alone PV powered gate

Fig. 6.108 Module locking devices (*left*) traditional bolted clamp, (*centre*) cleat and allen bolt (*right*) security bolt

protection was easily circumvented as the thieves pried the modules out of the supporting guide frame.

Marking, Tagging and Registering

Making sure that all solar collectors are in some way unique can often be a deterrent to some thieves. Many solar wineries have opted to mark their modules, for example using non-removable paint or engraving to mark the name of the winery on the frame. This, whilst offering some level of deterrent, may take time, particularly if there are a significant number of modules to be marked. A more popular method is to have all module serial numbers noted at time of installation so that in the event of theft, a missing module list can be produced (Fig. 6.109).

Visual Monitoring

Security monitoring can be as simple or complex as necessary. In simplistic terms the security may rely on the diligence of winery staff to 'keep an eye' on the

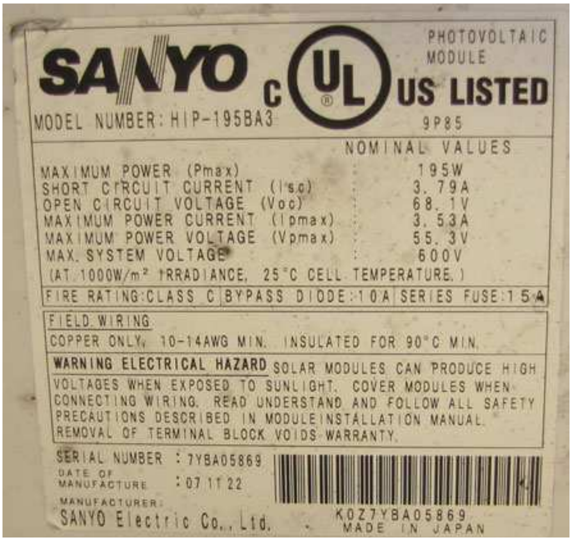


Fig. 6.109 Module serial number

system or security personnel may be instructed to check on the system periodically. Generally, however, this form of monitoring relies on human intervention and this is not always consistent. In some solar winery installations, closed circuit TV (CCTV) is used to provide 24 h recorded coverage of the systems, in particular the modules. This system may or may not be continually monitored. With constant monitoring any criminal act can be immediately observed remotely and dealt with accordingly. If it is not continually monitored, but the data is recorded, then it forms a basis in identifying and securing a criminal conviction in the future. Either way, the mere presence of the cameras may serve as a visual deterrent to any criminal intent (Fig. 6.110).

Security Alarm Systems

PV installations represent a significant financial investment and many wineries have taken quite extreme measures to ensure that their investment is protected. Increased protection usually means higher system cost. Typically, a full security system can add an additional 1–2% onto the PV installation costs, leading to longer payback periods. The type of systems employed utilise a range of sensor formats (volumetric, linear or contact), typically with a local alert (visual and/or audible alarms) with perhaps a telephonic connection to the local police or security provider. The alerts may be immediate with local warning to the thief or silent to permit intruder entrapment. Figure 6.111 depicts a corner fixing of linear sensor arrangement whilst Fig. 6.112 shows a volumetric PIR sensor. Any unwanted interruption of the beam will ensure that intruder activity is detected and a signal sent to the CPU with the appropriate response activated.

Fig. 6.110 CCTV monitoring of a ground mounted installation

Fig. 6.111 Corner fixing of linear sensor arrangement covering a solar winery installation

Akin to security fire arising from a PV installation can be an issue, particularly if it is installed on or near to the winery buildings. One case reports of a 'very small electrical fire' that broke out in solar installation, in a well known winery in Paso Robles, California [1]. In this case, during what was reported as 'module installation', a fire broke out on the roof of 'the red fermenting building' and seemed to be coming from the solar installation. The fire was contained shortly after and was concluded to be due to wiring issues.

6.3.6.2 Solar System Washing

It is very important that collectors are regularly cleaned, particularly PV modules, as the accumulation of dirt can have a significant, detrimental impact on the system performance. The winery environment is typically a very dusty environment, usually following long hot dry spells. In addition, solar installations in

Fig. 6.112 PIR volumetric sensor covering a solar winery installation

Fig. 6.113 Dirty PV modules on a ground mounted vineyard array

wineries may be affected by plant debris (leaves, sap, seeds, etc.), insect activities, water staining, bird droppings and various moulds. Figure 6.113 depicts how soiled a PV array can become.

There are various mechanisms employed by wineries to keep their PV installations operating at their optimal performance. For most wineries, this means cleaning/washing every 2–3 months, particularly at the end of the summer period. The washing process is typically a manual process. Staff members (or contracted personnel), armed with soft brushes and buckets containing a mild water and soap/detergent mix, will firstly remove any large debris before lightly washing the surface of the modules (Fig. 6.114). Stubborn stains usually require a little bit more effort. If the winery has been well designed, a water hose connection is located close to the array (Fig. 6.115) whereby the modules can be rinsed to reduce problems with staining. In many wineries this obvious point is overlooked in retrofit installations, resulting in additional effort to bring a water supply to the solar collector mounting location. The winery may also want to consider water quality, for example bore hole or well extracted water may be high in TDS and other

Fig. 6.114 Manually washing dirty PV modules on a roof mounted system

Fig. 6.115 Access to water supply

precipitants which may result in a staining or film build up on the module surfaces. In some situations, wineries have invested a rainwater harvesting system to collect and store water dedicated to module cleaning applications. In addition, it is advisable to carry out the washing process at a time when the solar is lower in the sky or it is not as hot so as to reduce rapid evaporation from the surfaces and thus residual films. The tilt angle has an influence in water run-off. A horizontal array can lead to pooling and thus greater stain accumulation. When washing the modules, it is also important to clean the fixing and mounting systems as well.

The time and effort (cost) in washing the modules increases with size and in very large systems, the winery may be forced into considering an automated system. To date, no wineries have invested in a fully automated system, although some have utilised frost protection sprinklers adapted to cover the modules

Fig. 6.116 Adapted frost protection sprinkler head for PV module washing

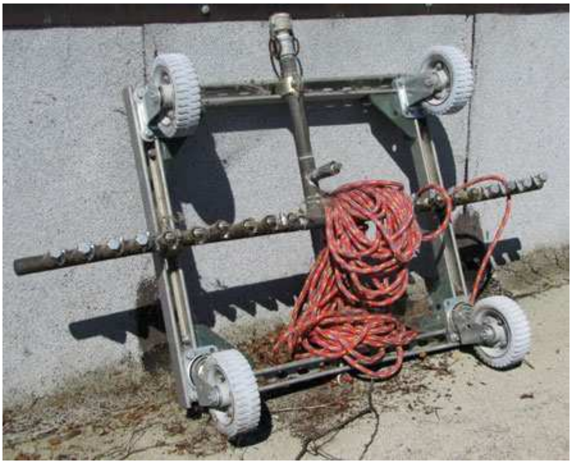


Fig. 6.117 Washing trolley to wash difficult to reach modules

(Fig. 6.116). Accurate Solar Power have produced the SolarWash, an automated, fully programmable and reliable washing system tailored to the needs of PV installations.

Specialised robots designed specifically to clean PV modules are now available. They are designed to cross the PV surfaces autonomously, washing debris from the module surfaces and frames. A Swiss firm, Serbot AG, currently has a family of 'Gekko' robots that are equipped with a range of cleaning attachments (such as brushes and wipers) to efficiently clean delicate PV modules.

Generally, ground mounted systems offer easier access to washing but in many instances the solar system is located in the vineyard, remote from a water source, making the washing process slightly more difficult. Roof mounted systems offer more difficulty based on access. Firstly there is the issue of roof access, complicated with differing roof angle, collector tilt and utilised space. Added to this you

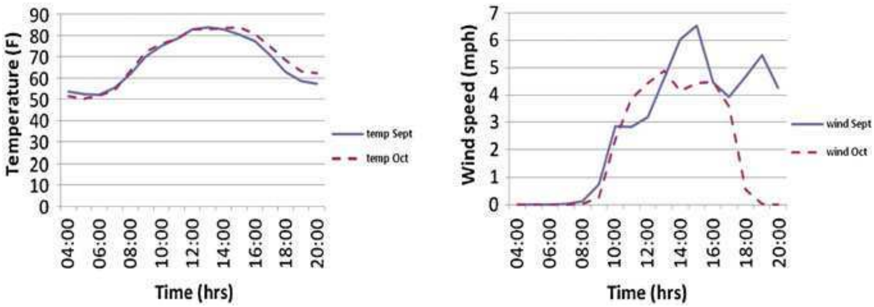


Fig. 6.118 Variation in temperature (*left*) and wind speed (*right*) on days before and after module washing

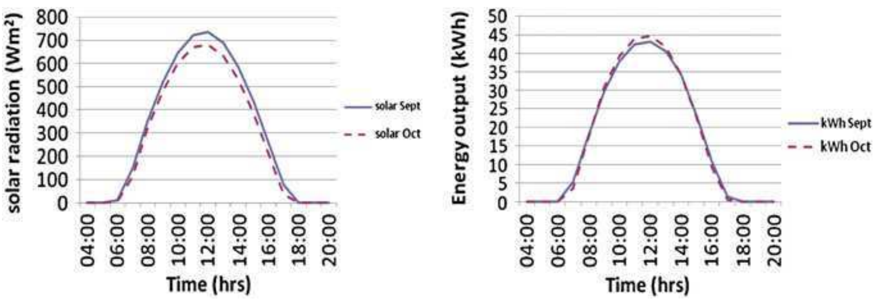


Fig. 6.119 Variation in solar radiation incident on the system (*left*) and difference in average hourly kWh output (*right*)

have members of staff or external contractors working at a height, washing an energized high voltage electrical system. Thus, safety becomes very important. Secondly is the availably of space on the roof. In many cases, due to the need to fully cover an available space with the maximum number of collectors, problems in cleaning the modules can occur, particularly those modules that are located in the centre of a large array. It should be good practice to take into account brush reach to allow for full cleaning coverage. In some winery installations this is present but there are a number of installations where this has not been considered and cleaning remote modules have been a continuous issue. Innovative mechanisms have been developed to counteract this problem. Figure 6.117 details a wash trolley, with a nozzle manifold, specifically made to deal with the issue of hard-to-reach modules. The trolley is simply positioned in line with the modules to be washed and slowly pulled across.

In a study of a Californian winery, a 76.4kWp DC roof mounted system covering an area of approximately 495 m^2 was monitored. The modules were washed in late September with the last wash being conducted 3 months previously. The operating conditions and performance where observed before and after washing. Figures 6.118 and 6.119 indicate the variation.

Fig. 6.120 Spray down to reduce dust movement in the vineyard/winery

Although there was a 10 day gap between the presented days and thus variation in the total incident solar radiation on the system, it is clear that the cleaning process has a significant impact on the system performance. Both of the observed days had similar operating conditions. In late September, the average hourly insolation over the collection period was 399.2 W/m^2 and the average hourly temperature and wind velocity was 71.9°F and 3.07 mph, respectively. During early October, the average hourly insolation over the collection period was 359.5 W/m^2 and the average hourly temperature and wind velocity was 73.3°F and 2.54 mph, respectively. However, both days yielded an average hourly output of 22.04 and 22.2 kWh respectively. The system in early October, after cleaning, with a lower solar input yielded more energy, almost 11.8% more energy. Drops in overall yield of greater than 20% are not uncommon.

In an effort to keep dust, and thus coverage of the modules, to a minimum, many wineries employ a spray policy. Periodically, the winery will spray water over dusty areas in an effort to reduce the effects of vehicle movement and wind from blowing excess dust onto the arrays. Figure 6.120 details this action in operation just above a PV array and Fig. 6.121 shows how careful placement of plants and foliage can be beneficial in reducing dust travel. Care must be taken to ensure that shading is not an issue.

The fungi *Aspergillus Niger* is common in many wineries. Ever present in the soil, it is easily transported indoors where its impact can be seen through characteristic black staining on exposed surfaces. When extracted via the winery HVAC exhaust system it can be transferred onto the roof where it can cover roof module solar collectors (Fig. 6.122).

Snow can be an issue in some wine producing regions of the world. Figure 6.123 illustrates the issues arising from a snow fall. In this Italian winery, with a PV installation rated a 382.8 kWp, the installation only yielded approximately 400 kWh on a day with significant snow fall and subsequent module coverage and yet had yielded nearly 1200 kWh on the days preceding the snow event.

Fig. 6.121 Landscaping used to minimise dust transfer onto PV installation

Fig. 6.122 Images of roof staining due to the fungi *Aspergillus Niger*

Water and condensation build up can also be a factor. This is particularly prevalent where reflector structures are used. Figure 6.124 shows a parabolic trough reflector with condensation build-up on the mirror in the early morning. This was not seen to represent a significant problem as the condensation quickly evaporated once the reflector was brought into alignment with the sun.

6.3.6.3 Solar System Operating Temperature

All PV module output power reduces as the module temperature increases. This is not a problem that is unique to winery installations. Under full solar exposure, a PV module will heat up substantially, reaching temperatures as high as 85°C. Higher module temperatures will reduce the voltage by 0.04–0.1 volts for

Fig. 6.123 Snow coverage of PV modules in an Italian winery

Fig. 6.124 Condensation build-up on a reflector surface

every 1°C rise in temperature, which can result in a module efficiency loss of 3–5% [2]. Figure 6.125 depicts a ground mounted PV installation in a US vineyard that has been observed both visually through the naked eye and using an IR

Fig. 6.125 Hot spot detection using IR camera imagery (*left*) normal image and (*right*) the same modules viewed through the IR camera

camera. In this example, on a moderately sunny day in early September, the modules were no higher than 39°C, which was still above the standard ideal of 25°C.

Ensuring that the modules are adequately cooled is one way in which the PV installation can be maintained so that it may operate at its system specific optimal output. Creating air movement across both the back and front of the modules is the most cost effective method in providing some form of cooling and module exposure is the key variable. The impact of temperature induced performance loss depends on the module mounting system.

Ground mounted installations (pole mounted or rack mounted) are exposed, permitting ambient air circulation on both sides of the module, providing a simple passive cooling effect (note: wind loading can now become an issue). Winery mounted systems, primarily roof mounted, can create a stagnant zone of air in and around the modules, leading to a smaller cooling effect. On flat roof installations, using a rack mounted structure, the cooling effect will be similar to a ground mounted system; perhaps even greater due to the elevated position. Flush roof mounted systems, however, are where elevated module temperatures can be problematic. Many wineries prefer flush mounted installations for reasons of aesthetics and convenience. In many instances, the mounting only provides a gap of 100 mm between the modules and the roof which is insufficient for good ambient air circulation. Furthermore, during the day the roof heats up, exacerbating the problem. BIPV installations, depending upon the level of fabric integration, provide even less circulation space, although they may get some level of cooling to the backside of the module as they are in direct thermal contact with the often cooled winery space below. In nearly all winery situations, it is not cost effective to provide some form of active cooling mechanism.

In the PVT system, detailed in Fig. 6.126 utilising a parabolic trough concentrator, active cooling is necessary. The system utilises a combined PV/thermal receiver, designed to produce power and hot water for the winery. However, to maintain a suitable PV operating temperature, without ensuring a significant drop

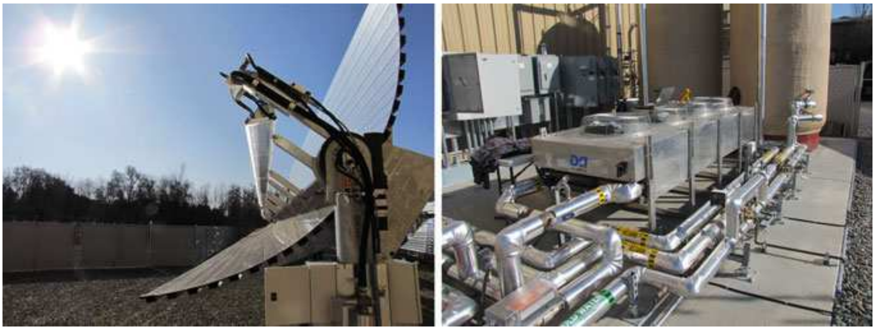


Fig. 6.126 PVT system with active cooling to maintain PV operating temperature with a maximum of 50°C

in performance, hot water is produced at a temperature not greater than 50°C. If the winery hot water store (which is over-sized to reduce the possibility of such an event) becomes saturated (i.e. is at 50°C), then solar collected heat is dumped to ambient via a fan cooled heat exchanger, to ensure optimal PV power production. The air cooled heat exchanger has 4 fans connected in series, with a ‘ramping’ operation in place to deal with an increasing heat dump demand.

Some wineries, from reasons governed more by the availability of suitable PV mounting space rather than developing a suitable module cooling strategy, have inadvertently arrived at an improved module cooling arrangement. ‘Floatavoltaics’, due to their proximity to a large body of water, take advantage of the localised cooling effect from surface evaporation from the ponds. Both the Far Niente and Gundlach Bundschu Wineries in California measured the module temperatures above the pond. In Far Niente’s case, the body of water cooled the modules and created module temperatures 2.8°C less than the adjacent land based modules.

6.3.6.4 Flora and Fauna

In most instances solar installations will operate efficiently and effectively without any ill effects from the local indigenous flora and fauna. It would, however, be remiss to fully ignore the impact that local plant and animal life can have on the performance of a solar collector and thus it is important that some actions are taken to ensure that they do not develop into a significant problem. In the solar winery, due to what tend to be rural locations, there may be an abundance of ‘wildlife’. Even in mono-cultural agriculture, significant flora and fauna can still be present.

Perhaps birds and their droppings, to be more precise, can represent the largest single issue. Bird droppings, defined as a hard source of shading, can stop light from reaching the cell or cells. If even one full cell is shaded the voltage of that module will drop rendering the modules less productive. If enough cells are shaded the module will not convert enough energy and can, in fact, become a tiny drain of energy on the entire system. Figure 6.127 indicates the sort of nuisance that bird

Fig. 6.127 Impact of bird droppings

Fig. 6.128 Gas activated bird scaring device

droppings can create. In this example bird droppings have fouled a significant proportion of a PV module, used to power an automatic gate into a winery.

In addition to shading (and increased module heat absorption), bird fouling is unsightly and acidic, making it both an eyesore and damaging to the module materials. To remove this problem, passive and active measures exist. Passive measures such as adhering strips of flexible metal spikes onto the modules/arrays can be effective whilst bird scaring devices, commonly used in the vineyard to scare off birds and other animals from taking fruit can be an effective active measure. Figure 6.128 depicts a gas operated system commonly used in California.

Other issues arising may be related to animals utilising the solar installation as a temporary home. Various insects, birds and mammals, for example have been

Fig. 6.129 Insects nesting on the underside of a PV module (*left*) and a bird's nest behind an inverter

Fig. 6.130 The impact of burrowing animals on PV supporting foundations

known to nest in system components. On the lesser side, these activities may represent a housekeeping problem, but in some cases a hornet's nest Fig. 6.129 can represent a stinging danger to staff and personnel working on or near the facility. The bird's nest presents less of a risk, although they could indirectly cause problems related with debris build-up if left unchecked. In one case a family of mice nesting in an inverter caused major damage and thus downtime and cost. Snakes, certainly during the installation phase, have been highlighted by a number of solar wineries in California as being a hazard on some ground mounted PV locations (Fig. 6.130).

Plant life can also represent a problem. Seasonal (and growth) changes in foliage around the installation can create a shading problem, vine coverage can be added to this, as can falling leaves and debris. Continuous unchecked build-up of

Fig. 6.131 Weeds growing in between modules

organic matter (and associated moisture retention) can increase the effect of localised degradation and corrosion of PV installation components and can create an ideal nursery for young plants to develop. Certain plants can produce saps that can drop onto solar collecting surfaces, leading to a build up of sticky spots, which, unchecked and combining with dust and other debris, can represent a significant effort to remove at a later date.

Generally weeds are a low level problem but, unchecked, weeds have the ability to grow fast and cover collecting surfaces and restrict access to the system. This in turn has the knock on effect of creating a habit which is suited to local animals and insects. Plant root growth can have a detrimental effect on foundations and mounting structures. In some cases, the actual plants growing may represent a danger or health risk. The presence of poison oak and poison ivy in American vineyards and wineries can be a certain hazard for winery staff, particularly if they are sensitive to its effect. At a lesser level, the presence of weeds can have an impact on the appearance of the system, making the winery appear untidy or unprofessional. Many wineries have a regular schedule in which weeds are removed and good housekeeping in and around the installation is observed (Figs. 6.131, 6.132, 6.133, 6.134).

6.3.6.5 Water Retention

Water management in many vineyards is an important issue. For a winery with a solar installation access to water for module washing is not the only consideration. A large solar collector array can present a large impermeable surface area and, during heavy rain events, can lead to very localised flows of rainwater run-off. Figure 6.94 illustrates this issue only too well. However, this large surface area can also be turned into an effective rainwater collector. Some wineries have looked into capturing rainwater from the collectors and directing it to long-term water storage tanks or ponds. Figure 6.135 shows a purpose built structure (over the external fermentation tanks at the Sonoma Wine Company) that was to designed to

Fig. 6.132 Weeds growing beside an inverter

Fig. 6.133 Initial weed growth under collector field

Fig. 6.134 Poison oak growing near to a PV installation

Fig. 6.135 Purpose built structure to capture rainwater but also designed to mount a PV array

accommodate a future planned PV array but was also designed to capture rainwater and channel it to the winery's water store. PV arrays, in the form of the pond mounted 'Floatovoltaics', have been used to shade the pond and thus reduce surface evaporation.

6.3.6.6 System Monitoring and Public Awareness

As with any solar installation, the winery will want to evaluate the performance of their system so that they may gauge the return on their investment. It is also important so that the facility manager may be able to monitor the system operation and determine the optimal time to clean the modules or carry out remedial action if a malfunction occurs.

A wide range of solar PV monitoring systems are available ranging from quite simplistic to fully interactive packages. One of the most common forms of data retrieval available is the 'built-in' inverter display. In this format, the inverter locally displays variables such as the instantaneous AC output, cumulative daily kWh and cumulative lifetime solar production. Information such as the DC voltage, DC amps and AC voltage can also be displayed depending on the type of inverter. For many wineries, this monitoring approach is adequate in determining the system performance. In some instances a remote inverter monitor, via a wired or wireless connection on an internal monitor display, can show all of the above variables. Figure 6.136 shows a wall mounted remote monitor display used in a German winery.

In some cases the winery is interested in a continuous historical record of the solar system performance. In these cases a separate monitoring system is required. Depending on the inverter, (some SunPower and Xantrex inverters) a PC can be connected into the inverter where data can be periodically downloaded to a spreadsheet. A step above this form of monitoring is web based monitoring. Using a web browser, the real time solar production along with a system summary, detailed views, historical data analysis, alert notification and environmental metrics can be displayed. Figure 6.137 depicts some of the common monitoring packages (Fat Spaniel Technologies and Sunpower Monitoring) that can be used.

A further refinement on general system web based monitoring is string or even individual module monitoring and performance feedback. There are a number of these proprietary monitoring packages available, both in new installation and retro-fit application. One such example is StringWatch which is found in a general web based solar PV installation monitoring system called SunSpot. StringWatch

Fig. 6.136 Dedicated wall mounted remote monitor display

monitors the performance at individual module, string, combiner box and re-combiner box levels, automatically notifying the system administrator of any problems, ensuring that the installation functions at peak efficiency. Enphase energy offers another package that gives detailed system monitoring and feedback. Using Enphase energy's micro-inverter system individual module data, via the Enphase Envoy (EMU) communication gateway transmitted to the Enlighten website, can be continuously viewed and its performance and operation managed to maximise solar production.

For the winery there may be another additional reason for enhanced monitoring; namely public awareness and dissemination. The perception of a winery can be all important to the modern wine producer and there are many examples of wineries adopting a particular theme or architectural rhythm to help boost the image of the winery. Being for example, organic, bio-dynamic, sustainable, fish-friendly or green are all important viticultural or winery practices and it is important to state that to most wineries, these are not gimmicks. Wineries are passionate in following a particular method to producing their product but, given the competition involved

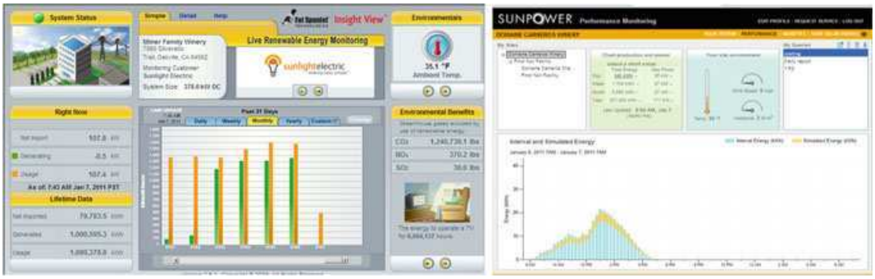


Fig. 6.137 Interactive web based monitoring packages (reproduced by kind permission from Miner family vineyards and Domaine Carneros)

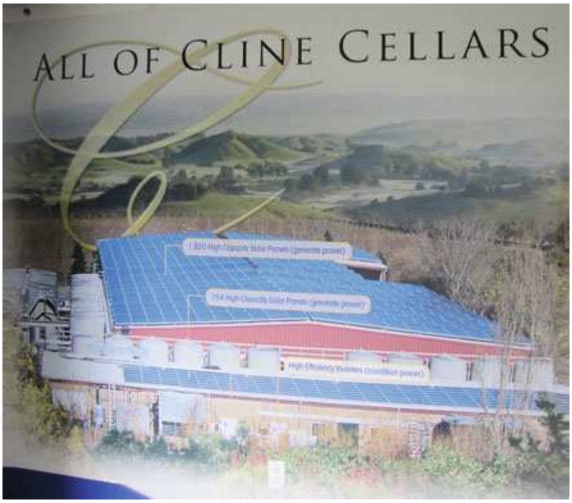


Fig. 6.138 Fixed poster presentation of a PV installation at a Californian winery

in selling wine, why not promote the fact that the winery is solar powered. Being environmentally conscientious (in combination with good economic sense) is a key element why many wineries have adopted solar and therefore it is important that this is conveyed to the public. The level of publicity varies significantly from solar winery to solar winery, some are happy with a basic level (perhaps a press release, website links and so on). In fact a number of wineries have not promoted the system at all and have designed a system that is completely hidden from view and the casual winery visitor may be unaware that the winery was solar. However, the vast majority are very keen to publicise the fact that the winery is 100% solar or solar powered or whatever is appropriate and use a variety of methods to do so. Key to this dissemination is some visual/public interface. This can be as simple as a poster or permanent display that gives the visitor some basic information about the system (background information, specification, images, performance and so on). Figure 6.138 gives an example of a poster display at a Californian winery.

Fig. 6.139 Console or wall mounted (interactive or visual)

Many wineries, however, due to the use of integrated monitoring software packages, have an interactive consol. Located in a prominent position, usually in the tasting or retail areas of the winery, the consol provides a real-time interface so that any visitor can access up-to-date information on the solar facility. Figure 6.139 presents a fully interactive pedestal consol with a touch screen interface and a simple wall mounted real-time performance display.

However, to be able to present this information, the site must be monitored. The monitored variables can be classified as being the meteorological data and the solar system data. The level of monitoring is dependent upon the system and the winery requirements. In many cases, just the solar system data is monitored whilst for sophisticated monitoring and control purposes, meteorological data is also monitored. The following is a list of the parameters that can be monitored in a typical winery installation:

- Incident global solar radiation, comprising direct (beam) and diffuse, on the horizontal plane or PV module plane.
- Ambient air temperature and module surface temperatures (front and back).
- Wind speed and direction
- Array output voltage, current and power (DC)
- Load/grid voltage, current and power (AC)

Figure 6.140 depicts two basic weather stations measuring total global solar radiation on the horizontal, ambient air temperature and wind velocity and direction. In addition, the pole mounted system is also measuring rainfall.

Like a photovoltaic installation, system performance monitoring of a solar thermal installation is equally important so that the winery may determine the energy supplied. Just like PV installations, a multitude of different systems exist. Figure 6.141 presents some feedback controllers for solar thermal winery installations. In a solar thermal installation, meteorological data may still be required but, to monitor and control the solar system, the collector circuit flow and return temperatures, collector circuit flow rate (and with the specific heat capacity of the heat transfer fluid, the collected thermal energy) and water storage temperatures are necessary. Furthermore, multiple storage temperatures can be used to determine

Fig. 6.140 PV installation meteorological data monitoring

Fig. 6.141 Solar thermal control and monitoring stations

tank stratification and, by monitoring the hot water supply variables, the solar saving fraction can be determined.

6.3.6.7 Guarantees and Warranties

Inevitably, any installed solar installation will have a finite span of operation. A well designed, installed and maintained installation should operate for 20 years or more (Fig. 6.142). However, as in any system, component failures, accidents and bad practice are to be expected. It is therefore important that any solar winery should invest in a guarantee or warranty scheme. Warranties typically come with a system but additional coverage can be purchased in addition to a standard warranty. There are three basic forms of warranties commonly applied to solar installations:

- Product warranty. These warranties cover system components. Typically, collectors can have guarantees that may be up to 25 years long. This can have much to do with the level of confidence manufacturers place in the longevity of their

Fig. 6.142 A replaced module for a faulty module covered by a product warranty

products. Inverters, however, may be the Achilles heal and, as previously reported, their failure whilst not regular, is not un-common. Warrantees on inverters tend to reflect this and can be as low as 1 or 2 years in some cases, an important fact not to be overlooked during the design and specification stage.

- System warranty. System warranties cover the proper installation and thus operation of system (and equipment therein) for a specific time period, usually 5–10 years. Not only do these warranties cover the system's safe and effective operation, they may also include a system performance guarantee.
- Annual energy performance warranty. System warranties cover the guaranteed output of the PV system. An energy performance warranty guarantees what the system will produce consistently over a period of time. Good metering and monitoring is essential to verify the system output and help the winery understand whether the system is operating properly or has a warranty related performance problem.

6.3.6.8 Easements and Access

An easement gives a party the right to get access through or use the property of another without possessing it. Easements can be classified as being one of the following:

- Right of way (easements of way)
- Easements of support (pertaining to excavations)
- Easements to daylight and air
- Rights relating to artificial waterways

In most circumstances the winery/vineyard is on private land and therefore it is not unusual for the grounds to be subject to one if not all of the above. Figure 6.143 shows two easements that have affected the physical design of the

Fig. 6.143 Ground easement (*left*) and air space easement (*right*)

solar installation. The installation on the left, due to the presence of overhead power lines, required the arrays to be designed in such a way to provide a 10 m wide easement to allow the utility provider sufficient access to bring equipment in under the power lines. This had the knock-on effect of ensuring that the PV installation was spread over a larger area of the hillside. The installation on the right, again relating to presence of power lines, required an air space easement. In this example, a carport PV structure was installed but because of the 240 kVA overhead power lines, the winery had to consider an easement allowance to ensure that the utility provider had sufficient access. The ensuing discussions required that the maximum height of the structure was reduced.

6.4 The 'True' Solar Winery

Globally, there are 293 wineries that are known to have a significant active solar collection system that can provide a significant energy input into the winery's operation, primarily producing solar electricity via photovoltaics. But what makes a solar winery? Many of the systems that have been presented in the previous chapter claim to be 100% solar….but do these wineries represent a true reflection of the solar winery? In many cases the wineries offset all of their electrical costs or kWh tally over the period of a year but rely on grid connection during peak loads or non-collecting periods and still require significant energy input via the combustion of fossil fuels for thermal requirements in the winery. Is this wrong? These wineries are contributing to the reduction in overall power production from the utility provider and furthermore the maximum solar resource typically coincides with the highest daily/seasonal electrical demand periods. To be a solar winery in the strictest possible definition of the term however, the winery should be able to

Fig. 6.144 Artist's impression of the sustainable winery (Teaching and Research Winery and the August A. Busch III Brewing and Food Science Laboratory) at UC Davis, California

operate without any grid or utility connection. For many this is a practical impossibility and it all comes down to the winery design.

Many of the presented wineries adopted solar after the winery had been in existence for some time and therefore, the installation was a retro-fit solution to meet the winery's energy requirement or was designed to take advantage of lucrative subsidies or feed in tariffs. Either way, the solar installation is designed to integrate into the physical or operational parameters of the existing winery infrastructure. In most situations, unless the system is significantly oversized representing a huge capital investment, the solar system is generally not capable of meeting the maximum demand during certain periods in the winery calendar or for specific winemaking activities and thus requires a utility power input in some capacity. Only new build wineries have the potential to fully embody the concept of a 'true' solar winery but this requires a significant evaluation of the winery design and operating practices at the very outset of the project.

The visionary concept for a sustainable (solar) winery developed by Professor Roger Boulton and his team [3] at UC Davis, California, is in the truest form…a solar winery. All energy used by the winery is (or will be when fully completed) solar derived. As previously stated, many wineries are 100% solar (powered) but only from a kWh tally over the year. More often than not, during peak load requirements the solar system is only able to provide a portion of the total load, the remainder being taken from the utility provider and given back at a time of surplus. To be truly 100% solar requires the system to be slightly oversized and incorporate some method of storing the collected energy. For solar PV systems this may mean batteries or some form of energy conversion and then storage. Solar thermal systems are much more adaptable in solar input, allowing collected energy to be stored and used at a time appropriate to the winery activity (Fig. 6.144).

The 3,160 m^2 facility at UC Davis, funded entirely by private donations, includes the teaching and research winery and the August A. Busch III brewing and food science laboratory. The building is designed to meet LEED (leadership in energy and environmental design) Platinum building and construction standards, the highest certification granted by the US Green Building Council. The new

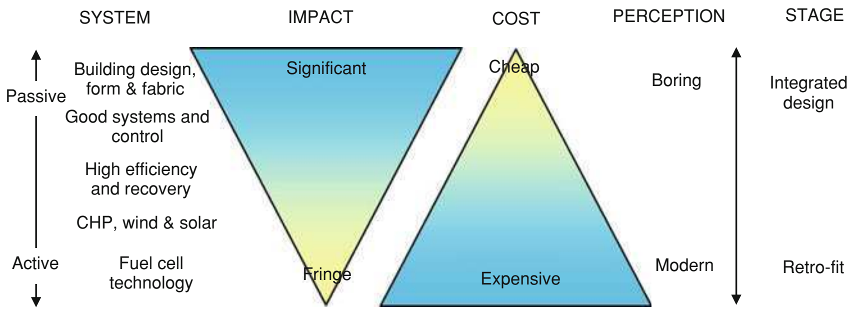


Fig. 6.145 Sustainable principles, building from the bottom up approach

Fig. 6.146 Teaching and Research Winery at UC Davis, California

building is founded upon good sustainable principles, building from the bottom up, as illustrated in Figs. 6.145 and 6.146.

The design of a solar winery begins long before any solar installation has been conceived. In order to fully embody the concept of sustainable design, the solar winery must first embrace the following:

- Removal of unnecessary energy usage
- Reduction of necessary energy usage
- Selection of the most energy efficient services, systems and equipment good energy load management
- And only then consider the
- Use of renewable (solar) systems

The new teaching and research winery and the August A. Busch III brewing and food science laboratory at UC Davis, California, follows all of these principles. From an energy perspective, the following is a list of the principles built into the design:

- Good site selection
- Building shape and form
- High-performance building envelope, exceeding current building codes to minimize heat transfer through the building structure

Fig. 6.147 The 200 l research fermentation tanks at UC Davis, California

- Good use and control of day-lighting (including shading and use of light roof finish to reflect unwanted solar gain)
- Energy efficient plant and systems, including fluorescents and LED lighting with good controls (daylight and occupancy sensors), good heat recovery from HVAC and refrigeration systems, efficient cooler compressor operation and natural ventilation with night-time purging
- Good maintenance and training awareness, with built-in scheduling

In addition, detailed consideration was given to:

- The materials and resources used in the building, with emphasis given to using recycled, regional and sustainable materials while minimizing construction waste
- Urban awareness to reduce the impact the building has on the surrounding location with attention to the urban "heat island" effect (good use of landscaping and vegetation, shading devices and reflective materials) and transportation (electric vehicle charging stations)
- Future proofing so that industrial advances can be accommodated by the building as flexibility has been built into the design so that it may adapt to demonstrate new best practices of sustainability. To this end, the winery was designed using a modular concept allowing new and developing systems to be 'plugged' into the winery operation.
- Indoor environmental health quality through good use of natural daylight, good user controls for comfort and monitoring of CO_2 levels
- Water efficiency. The primary focus was to reduce the use of water, which includes rainwater and process-water capture and reuse for landscape irrigation and sanitation needs. In addition to using water-efficient plumbing fixtures, the facility will use much of the energy generated on site to use RO continuously during the 6 months prior to harvest to filter enough rainwater to provide enough process water for the entire year. Tank cleaning will be CIP with recovery of the solutions over a 24–48 h period, but operating from storage. The water will be used between 10 and 12 cycles with a 90% recovery, effectively requiring 1/5th the volume (and 1/5th the cleaning chemistry). The domestic hot water and cold

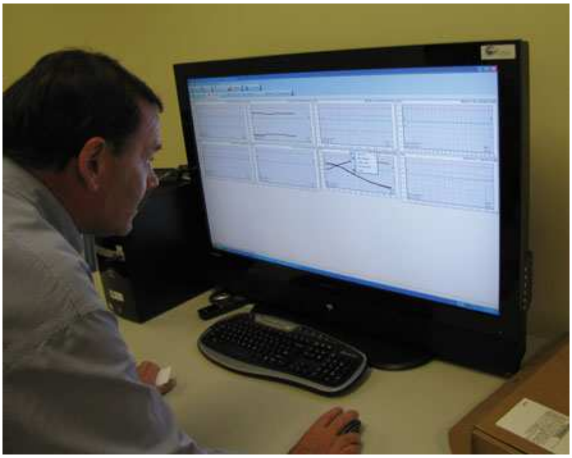


Fig. 6.148 Monitoring system at UC Davis, California

water systems are also small load, continuous systems with operation from storage rather than on demand.

The winery portion of the building covers an area of 1,160 m^2 and has a large experimental fermentation area with 152–200 l research fermentation tanks (Fig. 6.147) and 14 traditional 2,000 l fermentation tanks. CO_2 removal often requires a significant amount of energy to power the fans to extract the CO_2 build up. Indirectly this also extracts cooled or conditioned air, leading to heat gain, thus an additional cooling load. The new winery is designed with direct CO_2 capture from the fermentation process at the source. Each individual fermentor is connected to an extraction duct thereby collecting CO_2 without unnecessary waste and minimizing energy use. The system is also designed to sequester this CO_2, instead of releasing it into the atmosphere. The need for a large centralised refrigeration plant has been removed and instead a smaller plant supplies an ice store which provides a chilled water supply for all process activities in the winery.

Each of the 200 l fermentation tanks are designed on a modular basis, perfect for teaching purposes, but also efficient in operation. The facility boasts the latest in vinification monitoring. Real-time data from each individual fermentor can be accessed remotely and appropriate adjustments made to the fermentor depending upon the winemaker's requirements or preference (Fig. 6.148). Figure 6.149 shows the central stem, mounted on top of the tank. The stem device monitors the tank variables (temperature, Brix, etc.) and sends and receives information wirelessly. Various functions can also be activated such as heating and cooling, tank de-stratification and mixing, pump over during cap management or inputting wine process additives. Note the black insulating jacket, reducing heat transfer to/from the tank.

Three controlled-temperature rooms, barrel and bottle cellars, an analytical lab, a classroom and a special bottle cellar for donated wines complete the winery (Fig. 6.150).

Fig. 6.149 Integrated monitoring and service device on a 200 l research fermentation tank at UC Davis, California

Fig. 6.150 State of the art facilities at UC Davis, California

Unlike the solar winery at UC Davis, most wineries have not been designed to spread or minimize loads or to use storage systems for either thermal or energy needs. As such, there is a considerable mismatch in their use verses the solar PV output and often only meet 20 or 30% of the kW peak load. The UC Davis winery has been designed with a second building built into its operating concept that,

Fig. 6.151 One of the three roof mounted PV arrays at the UC Davis winery

when added to the existing winery facility (and building), will create a 'solar winery' in its truest form.

The second building, the Jess S Jackson facility, is also based on a modular concept and is designed to allow the winery to test and evaluate a range of systems and equipment that is new or emerging. A number of identical test bed rooms with full access to all winery service and utility networks are able to accommodate, for example, a new boiler or new centrifuge so that it may be tested in parallel with traditional systems. A full suite of monitoring devices and instrumentation is built into the facility. As a centre for providing practical and accurate testing and performance evaluation of systems that serve the winemaking process, it will be unique but more importantly, the winery will demonstrate the potential in sustainable winery design. The design will provide a blue-print for future proofing, ensuring that through a modular format, a modern winemaking facility can always be utilising the most appropriate systems without unnecessary disruption and unsustainable practices emanating from retro-fit installations. In addition, the building is also designed around good environmental practice and also includes passive cooling via berming and earth pipes, underfloor heating/cooling, fuel cell technology and hydrogen generation and storage.

Fundamental to the concept of being 100% self sufficient (from an energy perspective), is the winery's PV installation. Three PV arrays (Fig. 6.151) are flush mounted (at 15°) on the roofs of the teaching and research winery and the August A. Busch III brewing and food science laboratory building. A total of 442 CS6P-230 modules, rated at almost 102 kWp are connected to the inverters. The entire system was funded through a PPA and is estimated to produce 120,000 kWh/year. Once the additional winery building is fully operational, the PV installation will supply the building during peak load but surplus power will be used to generate hydrogen on-site using electrolysis which will supply the fuel cell once the solar input is reduced or gone, thereby avoiding batteries or a grid connection. By-product heat from the fuel cell will also be used on site and can be stored when not fully required.

Whilst this particular winery is not a true commercial winery, but rather a teaching platform for the University that operates on the principles of a commercial winery, the very fact that it was built on 'full-life' sustainable principles and operates from solar power alone, demonstrates that this type of winery design

is feasible. In this way, the winery serves as a role model for the wine industry and should be the benchmark for all future wineries to come.

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